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Contents

Vol. 9, No. 6, 2001

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Stratigraphy and Geological Correlation ISSN 0869-5938.

Pb–Pb Age of Limestones of the Middle Riphean Malgina Formation, the Uchur–Maya Region of East Siberia
G. V. Ovchinnikova, M. A. Semikhatov, I. M. Vasil'eva, I. M. Gorokhov, O. K. Kaurova, V. N. Podkovyrov, and B. M. Gorokhovskii 527

Origin and Development of the Cambrian Brachiopod Biochores
G. T. Ushatinskaya and Ya. E. Malakhovskaya 540

Regularities in Evolution of Jurassic Foraminifers
K. I. Kuznetsova 557

Benthic Foraminifer Zonation in the Campanian–Maastrichtian of the European Paleobiogeographic Region
V. N. Beniamovskii and L. F. Kopaevich 570

Palynological Characteristics of Paleocene Deposits in the Lower Volga Region (Borehole 28, Town of Dubovka)
G. N. Aleksandrova 591

Palynological Assemblages from the Middle Eocene Kuma Horizon and Its Age Analogues in Adjacent Regions
N. I. Zaporozhets 603

Critics and Discussion

Is the Thermoluminescence Method a Principal One for Correlation and Stratigraphy of Pleistocene Sections of Southern Tajikistan?
V. A. Bol'shakov 623

The Answer to the Critical Review by V.A. Bol'shakov
A. E. Dodonov 629

Personalia

Aleksandr Ivanovich Zhamoida (on Occasion of the 80th Birthday) 631

Author Index to Volume 9, 2001 632

Stratigraphy and Geological Correlation, Vol. 9, No. 6, 2001, pp. 527–539. Translated from Stratigrafiya. Geologicheskaya Korrelyatsiya, Vol. 9, No. 6, 2001, pp. 3–16.
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Pb–Pb Age of Limestones of the Middle Riphean Malgina Formation, the Uchur–Maya Region of East Siberia

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Abstract—The carbonate Malgina Formation, a constituent of the Riphean hypostratotype in Siberia, corresponds, according to paleontological evidence, to the terminal Middle Riphean horizons, and present-day geochronological data indicate that it is younger than 1300 ± 5 Ma and older than 1025 ± 40 Ma. Eight limestone samples (Mg/Ca < 0.066) selected for the Pb–Pb age determination contain less than 5.8% of silicate components and are insignificantly altered, as it is evident from geochemical criteria (Mn/Sr ≤ 0.2, Fe/Sr ≤ 5, Rb/Sr ≤ 0.001) and minimum difference between $^{87}Sr/^{86}Sr$ ratios (≤0.0007) measured in the primary and secondary carbonate phases. Secondary carbonates were removed using the step leaching of samples in HBr of variable concentration. The Pb–Pb age of 1043 ± 14 Ma (MSWD = 7.8) that is calculated for 18 data points characterizing various carbonate phases appears to be best approximating the time of early diagenesis in the Malgina limestones. With due account for stratigraphic position of studied samples, this and other Pb–Pb dates obtained for the Middle–Upper Riphean carbonate formations of the Urals and Siberia are concordant with ages measured by other methods and form altogether a regular series of five successive values. The Pb–Pb isochron dates of stratigraphic significance can be obtained only after a strict procedure of sample selection followed by the removal of secondary carbonate phases with the help of step-leaching method.

Key words: U–Pb systematics, carbonate rocks, epigenesis, Middle Riphean, Upper Riphean, Siberia, Urals.

Until the recent time, geochronological characterization of the Riphean hypostratotype in the Uchur–Maya region of East Siberia was limited by K–Ar dates obtained more than 30 years ago for mineralogically unstudied glauconite (*Geochronologiya dokembriya...*, 1968; Semikhatov and Serebryakov, 1983; and references therein). Dates obtained by modern methods have been published recently only for the upper Ui and Lakhanda groups of the Uchur–Maya section (Rainbird *et al.*, 1998; Semikhatov *et al.*, 2000). These results considerably changed the traditional view of isotopic ages characterizing not only the upper horizons of the section, but also the boundary between the Middle and Upper Riphean. Reliable dates obtained recently for older horizons of the section define the maximum age limit of the Kerpyl Group (Khudoley *et al.*, 1999, 2001) that predates the Lakhanda Group unconformably overlying it.

In this study, we had two objects in view. First, it was purposeful to determine the precision Pb–Pb dates for limestones of the Malgina Formation of the Kerpyl Group in order to broaden geochronological characteristics of the Riphean hypostratotype in the Uchur–Maya region. Second, the comparison between these and other Pb–Pb dates known for other Riphean formations of the Urals and Siberia (Ovchinnikova *et al.*, 1995, 1998, 2000; Semikhatov *et al.*, 2000) offers a possibility to evaluate the resolution ability of the Pb–Pb method and stratigraphic potential of corresponding age determinations for the Upper Precambrian carbonate rocks.

GEOLOGICAL POSITION AND AGE OF STUDIED SAMPLES

There are two different Riphean structures in the Uchur–Maya region (Fig. 1): the stable Uchur–Maya plate in the west and the Yudoma–Maya trough in the east that actively developed (Nuzhnov, 1967; Semikhatov and Serebryakov, 1983; Shenfil', 1991). These paleostructures with contrastingly dislocated Upper Precambrian and Cambrian beds (subhorizontal in the plate and deformed into large open folds in the trough, where they are complicated by faults and thrusts) also differ in thickness, accumulation environments, and, to a certain extent, in composition of coeval formations. The regional succession of Riphean deposits includes five groups separated by unconformities of variable significance (Semikhatov and Serebryakov, 1983; Shenfil', 1991). The basal Uchur Group spans the Lower Riphean interval. The overlying Aimchan and Kerpyl

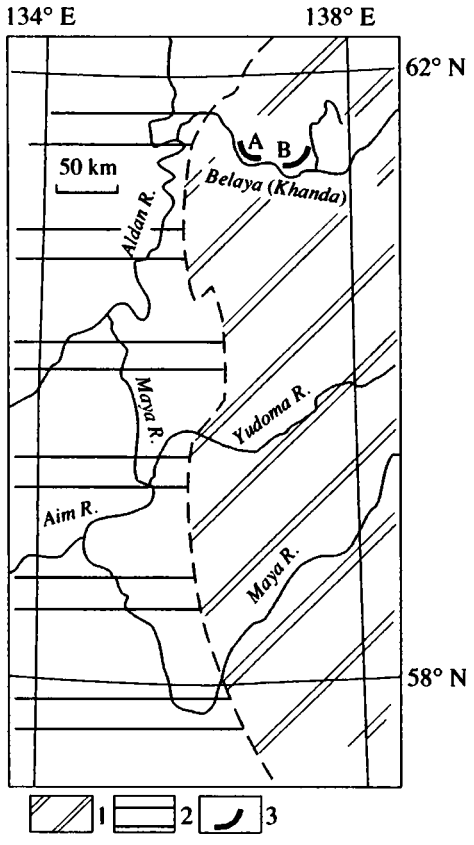

Fig. 1. Structural scheme of the Uchur–Maya region and localities of studied sections of the Malgina Formation: (1) Yudoma–Maya trough; (2) Uchur–Maya plate; (3) localities studied near the mouth of the Kurun-Mastakh Creek (A) and upstream off the Svetlyi Creek mouth (B), the right side of the Belaya River.

groups belong to the Middle Riphean, and the Lakhanda and Ui groups, which are terminal in the succession, correspond to the lower Upper Riphean.

The Kerpyl group that discordantly overlies either the older Riphean deposits, or the pre-Riphean crystalline basement, includes conformable beds of three subdivisions: the Totta Formation of siliciclastic sediments (450–1100 m thick), Malgina Formation of limestones (60–420 m thick), and Tsipanda Formation of dolomites (190–450 m thick). Samples studied in this work have been collected from two sections of the Malgina Formation, which are situated at the eastern and western limbs of the Gornostakhskii anticline in the northeast of the Yudoma–Maya trough and have been examined in coastal outcrops of the Belaya River (Fig. 2). The detailed description of both sections has been published earlier (Semikhatov and Serebryakov, 1983), and we present here only their general characteristics.

At the western anticline limb, we examined the Malgina deposits near the mouth of the Kurun-Mastakh Creek at the right side of the Belaya River. An upper part of the formation that is exposed here is about 70 m thick. It is composed of dark gray to gray fine-grained limestones displaying the microbial or fine horizontal lamination. The rocks have an insignificant amount of insoluble residue (0.5–4.5%). Along the contact with the overlying Tsipanda Formation, they are irregularly dolomitized at the epigenetic stage down to the depth of 50–55 m. Below this zone, limestones retain their original sedimentary textures and structures, being nonuniformly recrystallized into microsparite within small areas, which exhibit rare and diffuse patches of sparite and veinlets of secondary calcite. The underlying part of the formation (300–330 m thick) that is exposed upstream of the indicated site is predominantly composed of micrites intercalated with variably abundant interlayers of microbialites, calcisiltite, and rarer flakestone. Near the base, there are interlayers of clayey limestone and laminae of shale. Coloration of this rock succession gradually changes from dark gray in the upper part to pale-yellow and greenish gray in the middle one, and then to pinkish gray and cherry-red near the base. All the listed rocks are slightly recrystallized (small dispersed patches of microsparite and widely spaced calcite veinlets).

At the eastern limb of the Gornostakhskii anticline (Belaya River banks upstream off the Svetlyi Creek mouth), the Malgina Formation is up to 420 m thick. Its basal member (40–42 m thick) is composed of greenish gray, pinkish, and pale-yellow flaggy limestones having fine microbial lamination and intercalated with fine laminae (1–3 mm) of greenish gray shale. Near its base, there are, in addition, interlayers of clayey limestone and marl. The content of siliciclastic fraction varies in these rocks from 7.3 to 13%. Greenish to pale-yellow beds of micro-grained limestones above this member are 140–160 m thick in total. They enclose laminae of pale-yellow microbial limestones. The formation section is crowned with the 220-m-thick succession of dark gray bituminous micrites, which contain an insignificant siliciclastic admixture (0.6–2.2%) and locally enclose thin lentils of black cherts. Outside the zone of secondary dolomitization, all rocks of the Malgina Formation show micritic and subordinate microsparitic textures. Patches and veinlets of secondary recrystallization are scarce. Micritic limestones do not exhibit cathodoluminescence. Microsparites show a weak nidal luminescence within carbonate veinlets.

In the Yudoma–Maya trough, the Malgina sediments accumulated in the comparatively deep settings (below and above the storm wave base) of the distal shelf under condition of the quick rise and subsequent slow drop of sea level. Compositional changes in sediments suggest that the noticeable inflow of clayey material from the west into the basin took place at the very beginning of the Malgina time. By the end of this time, there were local anoxic environments in the basin, as it is evident from presence of rather thick (up to 5–10 m) packets of black limestones and clayey–calcareous shales enriched in organic matter, which appear near the for-

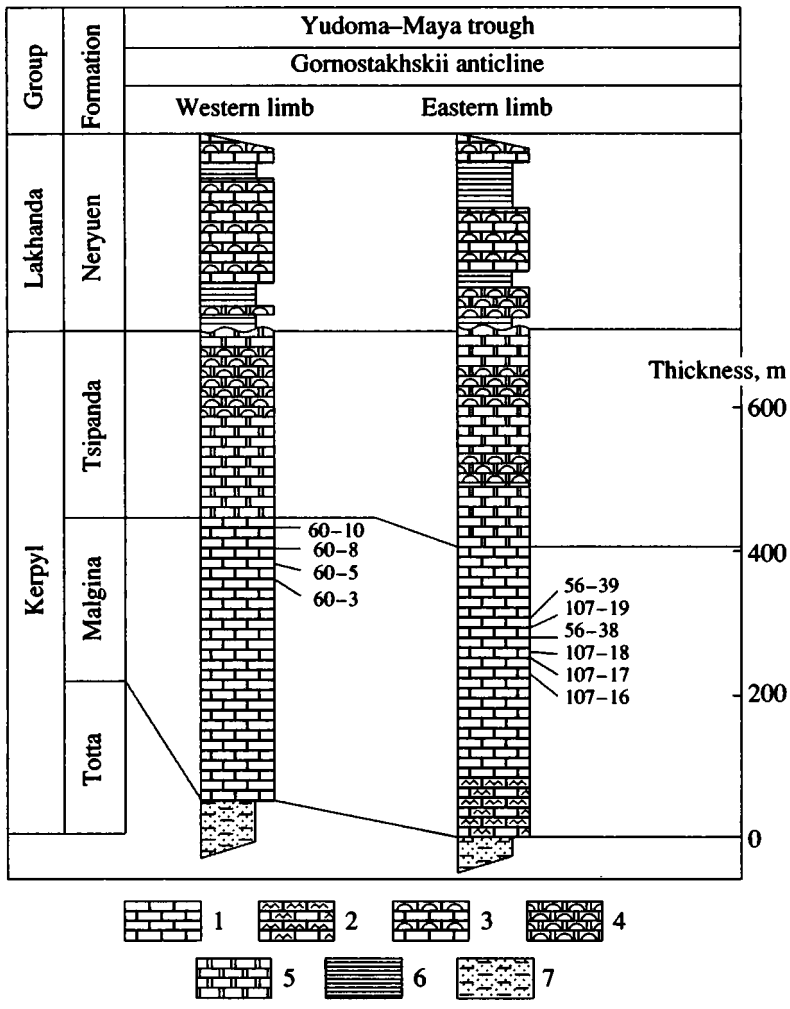

Fig. 2. Studied sections of the Malgina Formation with indicated sampling levels: (1) limestone; (2) microbial limestone; (3) stromatolitic limestone; (4) stromatolitic dolomite; (5) dolomite; (6) shale; and (7) siliciclastic rocks.

mation top in some sections of the Uchur–Maya plate and Yudoma–Maya trough (Semikhatov and Serebryakov, 1983). The maximum C_{org} content in such rocks (20.7–26.0%) is recorded in the Maya River middle courses (*Litologiya...*, 1980).

Age limits of the Kerpyl Group are established on the basis of paleontological, geochronological, and chemostratigraphic studies that yielded agreeable results.

Paleontological data point to an important compositional renewal of stromatolites and organic-walled microfossils across the Kerpyl–Lakhanda boundary. In addition to endemics, the Kerpyl Group encloses some transit Middle–Upper Riphean forms and rare taxa of stromatolites (*Omachtenia omachtensis* Nuzhn.) characteristic of the Lower Riphean Uchur Group. In addition, *Minjaria sakharica* Kom. et Semikh. and *Telemsina* sp. from the Kerpyl deposits are local representatives of form genera characteristic of the Upper Riphean in the Urals and North Africa. At the base of the Lakhanda Group, transit stromatolite taxa become much more diverse and associate with newcomers *Inzeria tjomusi* Kryl., *Jurusania cylindrica* Kryl., and *Baicalia lacera* Semikh., which are typical of the lower Upper Riphean horizons in several regions (Krylov, 1975; Semikhatov and Serebryakov, 1983; Semikhatov, 1995). Most remarkable among these taxa is *B. lacera* whose microstructure is also known as characterizing representatives of other morphotypes, which are widespread in the lower horizons of the Upper Riphean in many regions and mark the particular stage in evolution of cyanobacterial ecosystems and global environments of carbonate accumulation (Knoll and Semikhatov, 1998).

Much more impressive are compositional renewals in assemblages of organic-walled microfossils from the base of the Lakhanda group. Characteristic Upper Riphean forms appearing at this level are morphologi-

cally diverse acanthomorphic acritarchs *Trachyhystrichosphaera aimica* Herm., *T. stricta* Herm., and *Prolatoforma*; spiral-cylindrical *Obruchevella*; wide ribbons of *Plicatidium*; beaded *Arctacellularia*; fusiform *Pellicularia*; giant *Lakhandinia, Segmentothallus*, and *Eosolena*; remains of xanthophyte algae *Paleovaucheria*; thalluses of multicellular algae *Archaeoclada* and *Varioclada*; differentiated remains of lower fungi and their reproductive structures *Eosacchoromyces, Mucorites*, and others (Timofeev *et al.*, 1976; Yankauskas *et al.*, 1989; German, 1990; Veis *et al.*, 1998). These forms associate with abundant transit taxa inherited from the Totta Formation of the Kerpyl Group and deeper horizons of the section (Veis and Vorob'eva, 1992, 1993). Leaving aside simple representatives of these taxa, which are of negligible stratigraphic significance, we should mention others inherited from the Totta Formation, such as giant acritarchs *Chuaria*, tubercular *Pulvinosphaeridium*, elongated thalluses *Ostiana*, catenulate *Sphaerocongregus*, filamentous *Asperatofilum* and *Taenitrichoides*, multiserial sheaths *Polytrichoides* and *Eomicrocoleus*, branching thalluses *Ulophyton* and *Majaphyton*, and other complex and large morphotypes. Adverting to their morphology and size, some researches consider these forms as characteristic of the Upper Riphean (Veis *et al.*, 1998, 2000; and references therein). This viewpoint is however misleading, because all the organic-walled microfossils characterizing the Totta formation, have been found below the Upper Riphean deposits in the southern Urals and Cis-Uralian region (Veis *et al.*, 2000; *Stratigraphicheskaya skhema...*, 2000) and also in those deposits of the Anabar massif (Veis and Vorob'eva, 1993), which are of the Early Riphean age according to stromatolites and geochronological dates (Komar, 1966; Semikhatov and Serebryakov, 1983; Gorokhov *et al.*, 1991; 1997, 2001).

Available U–Pb dates of high precision define the age limits of the Riphean Kerpyl and Lakhanda groups of the Uchur–Maya region in a wide diapason only: the youngest population of clastic zircons separated from the Totta Formation is 1300 ± 5 Ma old (Khudoley *et al.*, 1999, 2001), whereas baddeleyite from diabase and gabbro-diabase sills in boundary horizons between the Lakhanda and Ui groups yielded the discordant age values of 1005 ± 4 and 974 ± 7 Ma (Rainbird *et al.*, 1998). Khudoley and his colleagues (2001) who analyzed the occurrence mode of these magmatic rocks concluded that they are localized in the lower part of the Ui Group and characterize the synsedimentary type of magmatism. Consequently, the aforementioned isotopic dates (1000–975 Ma) are likely to define the accumulation time of the lower Ui deposits. This conclusion is agreeable with the Pb–Pb date of 1057 Ma obtained for the youngest clastic zircon generation from these deposits (Rainbird *et al.*, 1998). The upper part of the Ui Group containing diabase fragments and discordantly overlain by Vendian strata is lacking reliable isotopic dates. At the same time, the Pb–Pb age of 1025 ± 40 Ma defines the time of early diagenesis for limestones from the lower part of the Lakhanda group (Semikhatov *et al.*, 2000). Accordingly, the Kerpyl group that is separated by the unconformable boundary from the Lakhanda group must be older than the latter age value.

Mineralogically unstudied glauconites from the Totta Formation that accumulated on the eastern, stably subsiding margin of the Uchur–Maya plate yielded the ordered series of K–Ar age values decreasing from 1170–1070 Ma in the lower formation part to 1070–1000 Ma in its middle interval, and then to 1020–970 Ma in the upper interval (*Geokhronologiya dokembriya...*, 1968; Semikhatov and Serebryakov, 1983). These dates have been traditionally regarded as indicating the accumulation (early diagenesis) time of the Totta sediments, but such an interpretation was doubted, when the U–Pb dates obtained for baddeleyite showed that the K–Ar dates for glauconites from the Lakhanda and Ui groups (960–870 and 760–700 Ma, respectively), which continued the aforementioned series of age values, are "rejuvenated." The considerable dispersion of age value characterizing the Totta glauconites suggests that K–Ar systems in some of these minerals were disturbed in the course of epigenesis. It should be added as well that Al-glauconites from lower and middle horizons of the Totta Formation sections in the Onmya Uplift located in the central part of the Uchur–Maya plate have experienced, according to their Mössbauer characteristics, the epigenetic structural transformations and yield the Rb–Sr isochron age of 864 ± 4 Ma that is distinctly "rejuvenated" (Semikhatov *et al.*, 1989). It is likely that the considerable age difference between glauconites collected from the Totta Formation in different areas of the Uchur–Maya plate is interrelated with variable geological history of individual areas. In any case, it is clear that the time range of the Kerpyl group is between 1300 ± 5 and 1025 ± 40 (1005 ± 4) Ma. At the same time, C-isotope chemostratigraphic data suggest that the Malgina Formation is younger than 1250 Ma, because important changes in the global biogeochemical cycle of carbon took place close to this date (Kah *et al.*, 1999; Bartley *et al.*, 2001): stasis of the global system that began 2060 Ma ago (Brasier and Lindsay, 1998) and was characterized by almost invariant $\delta^{13}C_{carb}$ values close to zero (0 ± 1.0 ‰ PDB) gave place to a period of their moderate variations from –2.0 to +3.0 ‰. In the Uchur–Maya region, this transition separates the Aimchan and Kerpyl groups. In the Aimchan carbonates, $\delta^{13}C$ values are close to 0.5 ± 0.6 ‰ and range in the Malgina limestones and their analogues of the Turukhansk area from –2.0 to +1.9 ‰ (Knoll *et al.*, 1995; Vinogradov *et al.*, 1998; Bartley *et al.*, 2001).

Thus, paleontological data suggest that the Kerpyl Group is terminal one in the Middle Riphean of the Uchur–Maya region. In addition, geochronological dates show that the basal Totta Formation of the group is younger than 1300 ± 5 Ma (U–Pb date for clastic zir-

cons). This formation presumably accumulated about 1170–1100 Ma ago (maximum K–Ar age of authigenic glauconite), whereas the overlying Malgina Formation is younger than 1250 Ma (C-isotope characteristics) and older than 1025 ± 40 Ma (Pb–Pb date for the lower Lakhanda limestones).

PROBLEMS OF U–PB AND Pb–Pb DATING OF SEDIMENTARY CARBONATE ROCKS

First attempts to determine the U–Pb and/or Pb–Pb age of carbonate rocks have been undertaken long ago (e.g., by Gerling and Iskanderova, 1976, for the Riphean carbonates of the Uchur–Maya region), but now they are of historical interest only because of a very low analytical level. The direct dating of marine carbonate deposits by U–Pb and Pb–Pb methods became possible much later, when the precision of mass-spectrometric measurements grew greatly and the level of laboratory contaminations was decreased down to the lowest notch (Moorbath *et al.*, 1987; Jahn and Cuvellier, 1994; Ovchinnikova *et al.*, 1995; and references therein). In the last decade, a considerable amount of Precambrian carbonate rocks was dated using these methods (Jahn *et al.*, 1990; Jahn and Cuvellier, 1994; Jahn and Simonson, 1995; Ovchinnikova *et al.*, 1995, 1998, 2000; Winter and Johnson, 1995; Russel *et al.*, 1996; Whitehouse and Russel, 1997; Toulkeridis *et al.*, 1998; Zachariah *et al.*, 1999). Nevertheless, some problems concerning the geochemical behavior of U and Pb in unmetamorphosed carbonate sediments restrict considerably their stratigraphic application.

The precision of U–Pb and Pb–Pb age determinations for dolomites and limestones directly depends on the variation diapason of initial U/Pb ratios in carbonate phases of these rocks. Magnitudes of these ratios are controlled by concentrations of both elements in sedimentation medium (seawater) and by distribution coefficients of U and Pb between carbonate minerals and seawater. The early diagenesis (the early dolomite formation after the high-Mg calcite included) results in redistribution of U and Pb between carbonate minerals and pore water: it usually decreases the content of U and increases concentration of Pb in carbonate sediments (Gobeil and Silverberg, 1989; Johnes *et al.*, 1992; Jahn and Cuvellier, 1994). As a result, the early diagenetic carbonates show much lower U/Pb ratios varying within a narrower range than in original carbonate sediments. Accordingly, the Pb–Pb ages of unmetamorphosed sedimentary carbonates mostly correspond to the resetting time of their U–Pb systems in the course of early diagenesis (Jahn and Cuvellier, 1994). At the same time, there are convincing sedimentological data (even for direct facies analogues of the Malgina carbonate rocks), which imply that the early diagenesis of Riphean carbonates was separated from their accumulation time by the geologically insignificant period (Maliva *et al.*, 1989; Petrov, 2000). Taking into consideration the analytical uncertainty, we may assume therefore that Pb–Pb ages obtained for Proterozoic limestones and early diagenetic dolomites are pretty close to the time of sedimentation.

The possibility of obtaining the stratigraphically significant U–Pb and Pb–Pb dates for Precambrian carbonate rocks is constrained by the following natural peculiarities of their U–Pb systems:

(1) Owing to the short residence time of Pb in seawater (Jahn and Cuvellier, 1994), the Pb isotope composition in the global ocean varies in space and with time depending on compositional changes in provenances.

(2) The irregular recrystallization of carbonate rocks at the early diagenetic stage may result in heterogeneity of Pb isotope composition in limestones and dolomites that could be perceptible on a scale of geological sampling.

(3) During the lithogenesis, carbonate minerals of sediments can be contaminated with U and/or Pb, which can be extracted from the associated silicate and sulfide admixtures, or mobilized by low-temperature fluids and meteoric waters from siliciclastic deposits present in the succession. Such a case is well exemplified by clayey limestones of the Upper Riphean Katav Formation of the Urals, which overlie the thick siliciclastic Zil'merdak Formation (Ovchinnikova *et al.*, 1998).

(4) As a rule, unmetamorphosed carbonate rocks of the Precambrian are to some extent inhomogeneous with respect to Pb isotope composition. The cause is that they all contain several carbonate phases, only one of which is early diagenetic, whereas others originated during the later stage (catagenetic in Russian and late diagenetic in English terminology) by interaction with media that had different Rb–Sr (Gorokhov *et al.*, 1995) and U–Pb systematics, i.e., different U and Pb concentrations and dissimilar Pb isotope compositions (Ovchinnikova *et al.*, 1995, 1998, 2000). One of the important factors of secondary alterations in carbonate rocks is their interaction with meteoric waters (Brand and Veizer, 1981; Banner and Hanson, 1990; Derry *et al.*, 1992; Gorokhov, 1996; Kuznetsov *et al.*, 1997; and references therein) that frequently leads to the U loss by carbonates, which become inappropriate for the U–Pb age determination (Asmerom and Jacobsen, 1993; Jahn and Cuvellier, 1994; Hoff *et al.*, 1995; Ovchinnikova *et al.*, 1995). At the same time, the resent Pb loss and the gain or loss of U do not change the Pb–Pb age of carbonates, and the last dating method has an advantage over the U–Pb method.

All the aforesaid implies that we should use first a complex of criteria to select the least altered samples of carbonate rocks potentially appropriate for the U–Pb and/or Pb–Pb dating. Afterward, we should extract the primary carbonate phases from those samples, which fit the selection criteria. Working with samples from the Malgina Formation, we used the published procedure of selecting the "best" samples (Ovchinnikova *et al.*,

1995, 1998, 2000; Vasil'eva *et al.*, 1998, 2000) on the basis of petrographic, geochemical, and isotopic criteria. Some deviations from this procedure are caused by specifics of the analyzed material (in particular, by absence of sulfide inclusions).

ANALYTICAL PROCEDURE

For the beginning, we sawed the macroscopically homogeneous limestone samples in two parts, one of which was used for chemical and isotopic analyses, and the other was examined by petrographic and cathodoluminescence methods. Petrography of the rocks was studied in thin sections. The cathodoluminescence characteristics are obtained using the "Camebax" microprobe at the Laboratory of Electronic Microscopy and Microanalysis of the "MEKHANOBR-ANALIT" Center, St. Petersburg. Chemical composition of rocks was analyzed at the Analytical Laboratory of the Geological Institute, Russian Academy of Sciences, using the atomic absorption spectroscopy for determination of Mn and Fe concentrations and wet chemical method for analysis of other components. In both cases, samples were dissolved in 1N HCl under the room temperature in order to leave intact the siliciclastic fraction of rocks.

According to results of chemical analysis, we selected 40 limestone samples among all others collected from the Malgina Formation, which had low content of silicate residue (≤13%) and Mg/Ca ratios ≤ 0.066. Petrographic and cathodoluminescent examination of these samples showed that they are lacking signs of significant epigenetic recrystallization and retain their primary textural and structural features. Only few samples from the western limb of the Gornostakhskii anticline, which exemplify upper horizons of the formation, turned out to be with microsparite patches visible against the general micritic background. Using then the strict geochemical criteria (Mn/Sr ≤ 0.2; Fe/Sr ≤ 5; Rb/Sr ≤ 0.001; Kuznetsov *et al.*, 1997), we selected 9 of these 40 samples, which appeared to be the least altered. The low alteration degree of finally selected rocks is also evident from data on their Rb–Sr systematics: the difference between the $^{87}Sr/^{86}Sr$ ratios, which were measured in leachates obtained after treatment of powdered samples in 1N ammonium acetate and in residues after leaching, turned out to be not greater than 0.0007. The only exception was Sample 60/8, for which this difference was 0.0011. In the selected samples, the content of insoluble residue usually ranged between 0.6 and 3.4% and never was greater than 5.8%. The residual fractions predominantly consisted of quartz and subordinate mica.

The non-cogenetic carbonate phases of different U–Pb systematics were separated using the three-step leaching procedure in HBr solution of various concentration under the room temperature. At the first stage, we treated the sample weighing during 30 minutes in 0.1N HBr, and 5 to 6% of the weighing entered the solution after this step. The carbonate phase that was leached at this stage is further designated as L-1. At the second stage, the first insoluble residue was treated again during 30 minutes in 0.25N HBr, and as a result, about 12% of its carbonate material entered the solution (phase L-2). The rest of carbonate material was finally dissolved during 24 h in 0.5N HBr (phase L-3). In the case of particular samples, we missed these treatment stages dissolving the bulk carbonate material in 1 N HCl to get the phase indicated as PCC-2. The silicate residue insoluble in HBr and HCl is indicated as the ISR phase. When it was necessary, we dissolved this residue in the mixture of concentrated HF and HNO_3.

Concentrations of U and Pb were analyzed using the isotope dilution technique and mixed $^{235}U + ^{208}Pb$ tracer. The Pb isotope composition was measured in aliquots without adding the tracer. U and Pb were separated from solutions using the ion-exchange technique with Bio-Rad 1 × 8 as described by Manhes *et al.* (1978). U and Pb isotope compositions were analyzed on Finnigan MAT-261 multicollector mass spectrometer using a regime of simultaneous measurement of all isotope ion currents. The measured Pb isotope ratios were corrected for the fractionation factor of 0.13% per atomic mass unit that was calculated from successive determinations of Pb isotope composition in NBS SRM-982 standard. The procedure blank during the period of our investigation was 0.05 ng for U and 0.4 ng for Pb. Raw U–Pb data were processed using the PBDAT program. Isochron regressions and weighted averages were calculated using the ISOPLOT program of Ludwig (1989, 1990). Calculating the isochron parameters, we took into account the errors reproducibility of 0.10, 0.15, and 0.20% for $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ ratios, respectively. These values are assessed by means of reiterated analyses of the BCR-1 standard. The Pb concentration in phases L-2 and L-3 of Sample 107/18 turned out to be extremely low, and Pb isotope ratios characterizing them are measured with greater uncertainty than in other cases. All uncertainty values are quoted in the text and Fig. 5 at the 2σ level.

RESULTS AND DISCUSSION

We studied the U–Pb systematics for eight "best" samples of the Malgina limestones, which were selected in accord with criteria described above, and also for samples 60/8 and 56/38, which show more noticeable signs of secondary alterations (see below). The analyzed sampling levels are indicated in the formation section (Fig. 2), and U–Pb data for studied carbonate phases are presented in the table. Samples collected at various levels of the section characterizing the eastern limb of the Gornostakhskii anticline (56/38, 56/39, 107/16, 107/17, 107/18, and 107/19) have higher U concentrations, greater $^{238}U/^{204}Pb$ ratios, and more radiogenic Pb isotope composition, than samples from

U–Pb data characterizing different carbonate phases of limestone samples from the Malgina Formation

Sample no.	Phase	Concentration, ppm		$\mu = {}^{238}U/{}^{204}Pb$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
		Pb	U				
56/38	PCC-2	0.634	1.506	227	54.123	18.185	37.892
	L1	0.171			19.967	15.840	38.401
	L2	0.457			43.497	17.394	38.008
	L3	0.402			58.349	18.498	38.099
56/39	PCC-2	0.768	1.412	140.6	33.033	16.709	37.789
	L3	0.605			34.376	16.819	37.968
60/3	PCC-2	0.520	0.0613	7.64	19.271	15.658	39.059
	L2	0.346			19.100	15.683	38.938
	L3	0.634			19.255	15.657	39.012
	ISR	3.34			19.002	15.664	37.834
60/5	PCC-2	0.772	0.0916	7.72	19.549	15.686	39.095
60/8	PCC-2	1.661	0.1072	4.22	20.157	15.745	38.740
	L1	0.450	0.0484	6.70	18.525	15.339	37.214
	L2	0.780			20.452	15.742	39.316
	L3	0.833	0.0695	5.49	20.377	15.741	39.133
60/10	PCC-2	0.601	1.146	174.9	48.694	17.814	38.820
	L3	0.632			50.030	17.991	39.128
107/16	PCC-2	0.702	2.34	391	76.347	19.951	38.535
	L1	0.145			22.802	16.030	38.294
	L2	0.591			59.666	18.631	38.116
	L3	0.772			74.663	19.816	38.363
107/17	PCC-2	0.530			79.981	20.172	38.215
	L1	0.275	1.312	311	20.628	15.771	38.168
	L2	0.159	0.849	627	76.619	19.982	38.492
	L3	0.243	1.214	672	95.532	21.354	38.468
	ISR	3.38	1.454	42.1	55.682	19.168	37.548
107/18	PCC-2	0.991	4.17	743	140.98	24.633	38.379
	L1	0.059	3.38	450	34.835	16.728	38.126
	L2	0.496	3.35	1210	144.81 (3%)	24.790	35.058 (2%)
	L3	0.420	2.24	985	149.90 (1%)	25.298	38.430 (0.13%)
	ISR	37.9	28.6	77.8	61.677	18.914	37.842
107/19	PCC-2	0.906	2.42	237	46.263	17.687	38.011
	L3	0.877			48.745	17.900	38.174

the upper member of the section exposed at the western limb (60/3, 60/5, 60/8, and 60/10).

The established variations of Pb isotope ratios in different carbonate phases, which were obtained by the step leaching of "best" samples and those that experienced secondary alterations (60/8 and 56/38), are illustrated in Figs. 3 and 4. The data point that characterizes average isotopic parameters of Pb incoming from external contaminating sources (water, air, aerosol, and dust) during the sample treatment (Hirao and Patterson, 1974) is shown in these figures as well. The Pb isotope composition of blank runs in our laboratory is within the same uncertainty limits: $^{206}Pb/^{204}Pb = 17.945$, $^{207}Pb/^{204}Pb = 15.324$, $^{208}Pb/^{204}Pb = 37.159$.

As one can see from Figs. 3 and 4, Pb that enters the first acid leachate (phase L-1) corresponds in isotopic parameters to the mixture of leads from external contaminating sources and from secondary carbonate phase dissolved at this treatment stage. Consequently, we should ignore all L-1 phases of limestones by the Pb–Pb age calculation. Babinski *et al.* (1995, 1999)

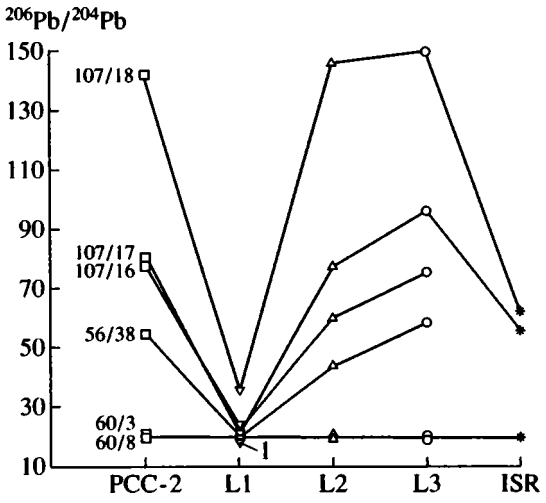

Fig. 3. Variation of $^{206}Pb/^{204}Pb$ ratios in carbonate and ISR phases of studied limestones. Data point 1 denotes the average $^{206}Pb/^{204}Pb$ ratio for external contaminating substances. Broken lines connect data points characterizing different phases of rock samples indicated by numbers at the left. Abbreviations indicating phases are explained in the text.

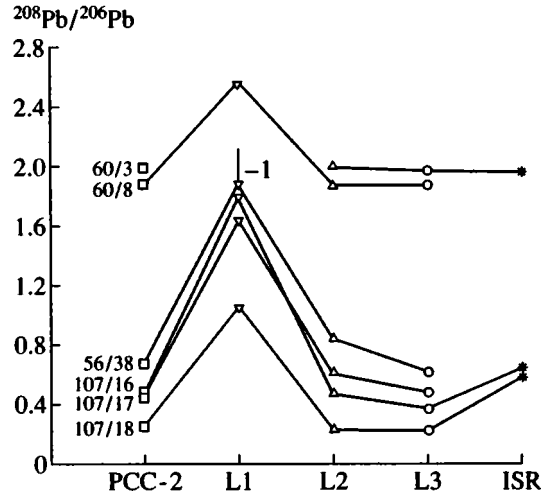

Fig. 4. Variation of $^{208}Pb/^{206}Pb$ ratios in carbonate and ISR phases of studied limestones. Data point 1 denotes the average $^{208}Pb/^{206}Pb$ ratio for external contaminating substances. Broken lines connect data points characterizing different phases of rock samples indicated by numbers at the left. Abbreviations indicating phases are explained in the text.

came to the same conclusion, when they studied Mesoproterozoic carbonate rocks in Brazil.

In samples from the eastern limb of the Gornostakhskii anticline, Pb in phases L-2 and L-3 is progressively more radiogenic than in corresponding weighings untreated in HBr. Apparently, the former are enriched in Pb of the early diagenetic carbonate and have a lower content of secondary carbonate material. As for Pb of silicate fractions (ISR phases), it is less radiogenic (beyond the measurement uncertainty) than in corresponding phases L-3. Accordingly, the carbonate phases successively leached from samples are either uncontaminated by Pb from associated siliciclastic material, or such a contamination is insignificant.

Samples 60/3 and 60/8 from the western anticline limb showed the comparable Pb isotope compositions almost in all their phases: in phase L-2 leached at the second stage, in phase L-3 enriched in primary carbonate, in phase PCC-2 leached by HCl from the whole rock samples, and even in insoluble residue (ISR phase). As compared to all other studied samples, limestones from this locality contain the least radiogenic Pb and show the lowest $^{238}U/^{204}Pb$ ratios, and we assume that the Pb isotope compositions in their carbonate and silicate fractions were equilibrated at the early diagenetic stage almost without the U gain. At the same time, the Pb concentration in Sample 60/8 that experienced considerable secondary alterations in terms of Rb–Sr systematics is noticeably greater than in other samples. It is likely therefore that post-diagenetic alterations were responsible for simultaneous Pb and Sr gain in this carbonate rock, the more so that the rock was sampled within a zone of irregular late dolomitization of the Malgina limestones along their contact with the Tsipanda Formation. Chaotic and irregular in shape areas of secondary dolomitization (Semikhatov and Serebryakov, 1983, Fig. 29) enable a suggestion that the less intense alterations interrelated with this process were also irregular in space and influenced Sample 60/8, but left intact others collected in the western limb of the Gornostakhskii anticline. Here, we should emphasize once again that data of cathodoluminescent analysis show that limestone samples from the site under consideration are recrystallized slightly stronger than in the eastern anticline limb, and that the recrystallization is of a distinct patchy character.

Sample 56/38 from the eastern anticline limb does not differ from other samples of this site in the trends of Pb isotope variations in various carbonate phases obtained by step leaching (Figs. 3 and 4). This sample is, however, comparatively depleted in Sr and shows the $^{87}Sr/^{86}Sr$ ratio that is higher than in neighboring samples collected 10 m above and 20 m below in the section. The relatively high degree of secondary alterations in this sample is also evident from distribution of data points characterizing its different phases, which significantly deviate from the strait line in Fig. 6. Taking into account all characteristics considered above, we excluded the results obtained for samples 60/8 and 56/38 from the data set used for the Pb–Pb age calculation.

In the $^{207}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$ diagram (Fig. 5), data points of L-2 and L-3 phases plot along a strait line within the sufficiently wide diapason of variables along

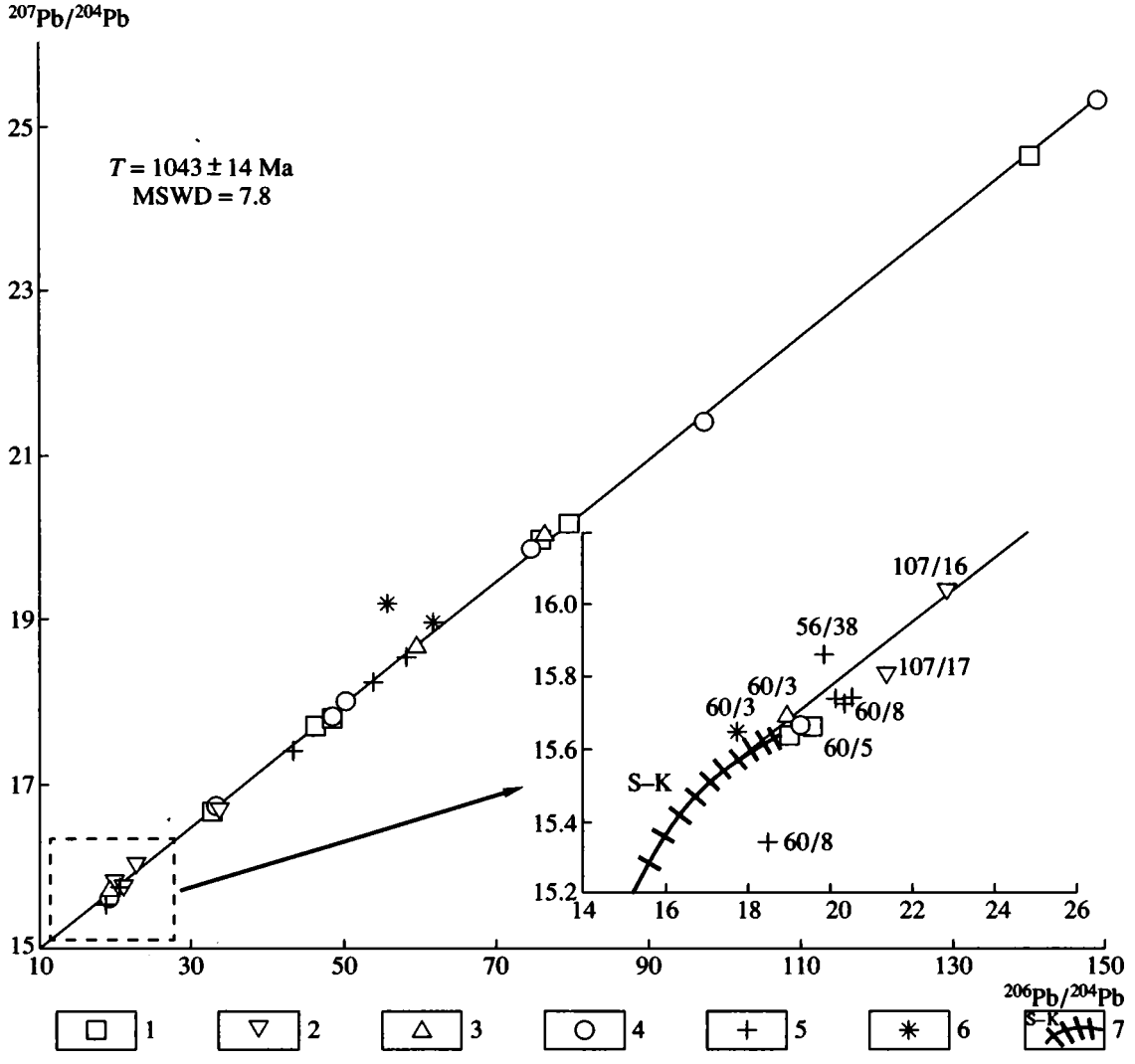

Fig. 5. $^{207}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$ diagram for limestones of the Malgina Formation: (1) PCC-2 phases; (2) L-1 phases; (3) L-2 phases; (4) L-3 phases; (5) all phases of samples 60/8 and 56/38; (6) ISR phases; (7) Pb accumulation curve, according to Stacey and Kramers (abbreviations are explained in the text).

both coordinate axes. The absence of correlation between Pb concentrations and $^{206}Pb/^{204}Pb$ ratios (see the table), and also between $^{208}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ ratios (Fig. 6), indicates that the regression in Fig. 5 is not the mixing line and has a geochronological meaning.

The Pb–Pb age calculated for seven data points characterizing L-3 phases, which are most enriched in primary (early diagenetic) carbonate material, is 1043 ± 38 Ma, MSWD = 13.5. For 13 data points of L-2 and L-3 phases, the calculated age equals 1048 ± 25 Ma, MSWD = 13. The regression line under consideration also approximates data points of bulk carbonate phases PCC-2, which were leached in HCl without treatment of samples in HBr. Consequently, despite possible effects of secondary alterations and laboratory contamination, these data points do not deviate from the errorchron to such an extent that would be greater than the summary experimental and geochemical uncertainty characterizing the regression line of primary carbonate phases. In this case, we can use PCC-2 phases for the Pb–Pb age calculation, thus having 18 data points defining the errorchron. The corresponding age value of 1043 ± 14 Ma (MSWD = 7.8) coincides, within the uncertainty limits, with the value calculated for seven carbonate phases of the Malgina limestones, which are enriched in primary carbonate material. The high MSWD value presumably is a consequence of the irregular, early diagenetic recrystallization of carbonate sediments.

Data considered above suggest an important conclusion. If the "best" samples are selected on the basis of

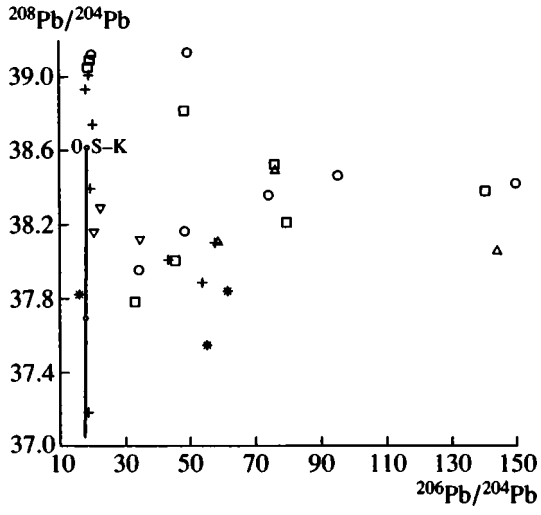

Fig. 6. $^{208}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$ diagram for limestones of the Malgina Formation (symbols as in Fig. 5).

strict geochemical criteria, the analysis of Rb–Sr systematic included, and if the share of non-cogenetic carbonate phases is small and insignificantly affecting the U–Pb characteristics of bulk carbonate material, then we can use PCC-2 phases, in addition to L-2 and L-3 phases, for the determination of Pb–Pb ages of carbonate rocks. In some cases, this offers a possibility to extend the variation diapason of measured Pb isotope ratios and to decrease the uncertainty of isotopic dating. This does not mean, however, that all whole rock samples of carbonates are suitable *a priori* for the direct Pb–Pb dating. First, we must test their appropriateness using the procedure of step leaching that allows us to separate primary and secondary carbonate phases, and to determine the degree of U–Pb system disturbance in carbonate rocks.

CONCLUSION

The Pb–Pb age value of 1043 ± 14 Ma calculated for the Malgina Formation is consistent with its stratigraphic position in the terminal Middle Riphean horizons and with isotopic dates, which are known for underlying and overlying Riphean subdivisions of the Uchur–Maya region and have been obtained using the U–Pb dating of zircon and baddeleyite (Rainbird *et al.*, 1998; Khudoley *et al.*, 1999, 2001). Among these dates, there is as well the Pb–Pb age of 1025 ± 40 Ma obtained for limestones of the lower Lakhanda Group (Neryuen Formation), which are located stratigraphically higher than the Malgina Formation.

Distribution of available isotopic dates in the section shows that thick carbonate successions representing an upper part of the Kerpyl Group and the whole Lakhanda Group accumulated during the comparatively short geological period of about 50–60 m.y. long. Together with the Middle Riphean Yusmastakh formation of the Anabar massif (Gorokhov *et al.*, 2001), these successions exemplify the quick accumulation of thick deposits on the Riphean carbonate platforms of Siberia.

In the context of this study, it is interesting to compare the aforementioned Pb–Pb ages of two carbonate formations of the Uchur–Maya region with the date of 1035 ± 60 Ma that was obtained earlier for dolomites and limestones of the Sukhaya Tunguska Formation exposed in the Turukhansk region of central Siberia (Ovchinnikova *et al.*, 1995). Paleontological and C-isotope chemostratigraphic data (Semikhatov and Serebryakov, 1983; Semikhatov, 1995; Knoll *et al.*, 1995; Podkovyrov and Vinogradov, 1996; Vinogradov *et al.*, 1998; Sergeev, 1999; Bartley *et al.*, 2001) show that the Sukhaya Tunguska Formation is terminal one in the Middle Riphean succession of the last region and occurs between stratigraphic analogues of the Malgina Formation and lower part of the Lakhanda Group of the Uchur–Maya region (Semikhatov *et al.*, 2000; Bartley *et al.*, 2001).

Accordingly, we have the following successive values of Pb–Pb ages characterizing stratigraphic succession of three Riphean formations (from the base upward): 1043 ± 14 Ma (Malgina Formation), 1035 ± 60 Ma (Sukhaya Tunguska Formation), and 1025 ± 40 Ma (Neryuen Formation of the Lakhanda Group). In terms of formal statistical criteria, difference between these dates is insignificant. At the same time, it is obvious that we have a series of values (probabilistic averages) diminishing in stratigraphic succession. Moreover, this series as a whole and each particular value are concordant with isotopic dates obtained by other methods.

This is a first known series of stratigraphically successive Pb–Pb dates obtained for carbonate rocks and characterizing the accumulation (early diagenesis) time of successive Upper Precambrian formations. Outside Siberia, this series can be continued by dates known in the southern Urals, namely by the isochron Pb–Pb age of 836 ± 25 Ma that is obtained for limestones of the Inzer Formation distinguished in the lower part of the Upper Riphean stratotype (Ovchinnikova *et al.*, 1998), and by the weighted average value of 780 ± 85 Ma that characterizes Pb–Pb ages of the Min'yar dolomites occurring in the upper part of the stratotype (Ovchinnikova *et al.*, 2000). Like in Siberia, both Pb–Pb ages of Riphean carbonate deposits in the Urals are consistent with dating results obtained for corresponding formations by other methods. Thus, despite a considerable analytical uncertainty of the method, the Pb–Pb dating of carbonate rocks is of reasonable resolution ability and can be informative with respect to the accumulation history of Riphean formations.

In order to obtain the isochron Pb–Pb ages of stratigraphic significance, it is necessary however to use the outlined strict procedure of selecting carbonate rock samples potentially appropriate for dating and to apply the step leaching to selected samples that removes sec-

ondary carbonate phases (and sulfide admixture, when needed). Using the leaching method, we avoid the systematic inaccuracy of age determinations that is related to involvement of age-variable carbonate phases having different U–Pb parameters in the isotopic analysis.

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Origin and Development of the Cambrian Brachiopod Biochores

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Abstract—Analysis of the origin and dispersal of Cambrian brachiopods shows that the initial differentiation of brachiopods into the Equatorial and Notal biochores took place in the second half of the Atdabanian. In the Botomian time, the vast Equatorial biochore was broken up into a number of areas that existed till the middle mid-Cambrian. Afterward, differences between the areas diminished, and new differentiation occurred in the second half of the Late Cambrian.

Key words: Cambrian, brachiopods, paleogeography, biochores.

Up to the mid-1960s, Cambrian brachiopods were not considered to be sufficiently abundant to have a biostratigraphic and paleobiogeographic value. According to the most comprehensive review of the Cambrian brachiopods (*Treatise...*, 1965), they comprise 36 genera with phosphate shells (Class Lingulata) and 27 genera with carbonate shells (Class Calciata). Most of the taxa were reported from the Upper Cambrian. Later on, 63 new genera of lingulates and 33 new genera of calciates were described. Accordingly, the number of valid Cambrian brachiopod genera increased more than twice. At present, 63 genera are known from the Lower Cambrian, 71 genera from the Middle Cambrian, and 75 genera from the Upper Cambrian, 96 of them representing the Class Lingulata and 70 the Class Calciata (table, Fig. 1). Brachiopods turned out to be the permanent components of Cambrian faunal associations in many regions. When summarizing all available data on stratigraphic and geographic distribution of Cambrian brachiopods, we made an attempt to distinguish the brachiopod biochores that appeared in the Early Cambrian and developed through the Middle–Late Cambrian.[1] The established biochores were initial provinces rather than realms of brachiopod fauna. The technique of graphic representation of secular biochore development was that suggested by Meyen (1984).

PALEOGEOGRAPHIC SITUATION BY THE EARLY CAMBRIAN

According to paleomagnetic records, there was a single paleocontinent Rodinia in the second half of the Proterozoic (Hoffman, 1991; McMenamin and McMenamin, 1990; Kirschvink, 1992; Powell *et al.*, 1993). Its larger part enclosed North America, northern Asia (the Chukchi Land, Siberian platform, Altai–Sayan foldbelt, Mongolia, Far East, Kazakhstan, and Middle Asia), North Africa, Near East, southern and partly northern China, India, Australia, and Antarctica. It was located in the equatorial zone on either side of the equator between 30°N and 30°S. Territories of the present-day North and East Europe, Newfoundland and British Isles, South Europe (a part), West Africa, and South America were located in the moderate and high latitudes of the southern hemisphere. In the Vendian time, the Rodinia broke up into gradually diverging large blocks (Hoffman, 1991). By the Early Cambrian, vast areas of the continent were occupied by epicontinental shallow basins. The Tommotian time was characterized by marine terrigenous, terrigenous-dolomitic, and terrigenous-carbonate sedimentation in the territories of the East European platform, South Europe, Newfoundland, western and eastern coasts of North America, North Africa, India, Australia, and the Altai–Sayan foldbelt. Carbonates associated with phosphorites accumulated predominantly in southern Kazakhstan, northern Mongolia, southern China, and Iran. Limestones with a small admixture of fine-grained terrigenous material were deposited in the Anabar–Sinskoe facial region (the transitional zone) of the Siberian platform (*Yarusnoe...*, 1984). This region was the first in the Earth history where archaeocyathids, molluscs, chiolites, different small shelly fossils (SSF) of unclear systematic position and, finally, brachiopods appeared in abundance in the earliest Tommotian (Rozanov *et al.*, 1969; Pel'man, 1977; Rozanov, 1984; Rozanov and Zhuravlev, 1992). Later on, the spatial distribution of brachiopods was determined mostly by location and connections of sea basins, and, as shown below, depended on abiotic environment, feeding mode, and possibility of dispersal.

Feeding Mode and Dispersal of Brachiopods

Main abiotic factors that affected the brachiopod habitation, such as sedimentation regime, basin depth,

[1] Table presents references to all publications used.

substrate, salinity, and concentrations of oxygen and suspended matter in seawater, are discussed in many publications (Rudwick, 1970; Zezina, 1976; and references therein). We consider here only some specific features of their feeding and dispersal, which differentiate lingulates from calciates.

Feeding. All brachiopods are typical filterers. There are some differences in feeding mode of recent articulates (calciates) and lingulates (Zezina, 1976). According to Chuang (1959), *Lingula unguis* that secretes some gastric ferments can use vegetable food, whereas recent articulates lacking this ability consume aggregates of bacterial cells and organic matter mass, but die at a long supply of phytoplankton (Atkins, 1960). Another distinctive feature of lingulids is a more effective ciliary mechanism of lophophore tentacles removing undesirable particles, which got inside with water (Chuang, 1956). Therefore lingulids are less sensitive to excessive suspended matter and can inhabit silted bottom areas. Articulates are less adapted to live in highly turbid water areas. Most likely, these specific features of feeding of phosphate- and carbonate-shelled brachiopods appeared as far back as in the Early Paleozoic and explain the presence of lingulates in coastal, locally silty areas rich in fine suspended matter and phytoplankton, on the one hand, and absence of carbonate-shelled forms in these areas, on the other. The latter forms preferred a hard substrate and active hydrological conditions.

Dispersal. Sessile brachiopods can settle in different areas in the larval form only. The lecithotrophic larvae of recent calciates can float loosely from several hours to one or two days before sinking to the bottom frequently near parent species (Zezina, 1976). The planktotrophic larvae of recent lingulates can float in water for few days to a month (Malakhov, 1976). Owing to this peculiarity, lingulates can be widely dispersed. Species of recent lingulid genera *Lingula* and *Glottidia* are widespread in shallow areas of the Indian and West Pacific oceans, and species *Pelagodiscus atlanticus* (Order Discinida) has a worldwide distribution. Larvae of this species were discovered in the plankton mass obtained from the surface and deep (2.4–3.0 km) oceanic waters (Zezina, 1976). Some Cambrian species of orders Paterinida, Acrotretida, and Lingulida have also the broad, occasionally subglobal distribution, presumably as a result of long pelagic stage of larvae development (Rowell, 1986). An indirect evidence for the long larval stage is the size of larval shells, which are not greater than 1/3–1/5 of mature shells of some Cambrian forms of these orders. In addition, larval shells of most Cambrian lingulids and all acrotretids have numerous surface cells. In opinion of some researchers (Popov *et al.*, 1982; Williams and Curry, 1991), this indicates a vesicular structure of periostracum that enlightens the larval shells and enables adaptation to the pelagic mode of life. Due to the different duration of the larval stage, lingulates may have larger area of distribution than calciates.

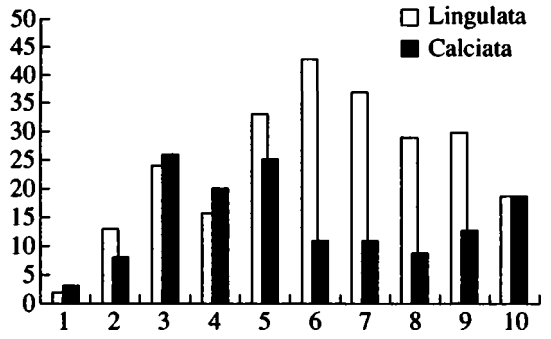

Fig. 1. Quantitative relationships between the Lingulata and Calciata genera throughout the Cambrian ages: (1) Tommotian; (2) Atdabanian; (3) Botomian; (4) Toyonian; (5) Amgian; (6) Mayan; (7) Ayusokkanian; (8) Sakian; (9) Aksayan; and (10) Batyrbayan.

Geographic Distribution of the Cambrian Brachiopods (see the table)

The Early Cambrian. As mentioned above, the earliest brachiopods appeared in the Anabar–Sinskoe facial region of the Siberian platform (*Yarusnoe...*, 1984). They belonged to the orders Paterinida (Class Lingulata, genera *Aldanotreta* and *Cryptotreta*) and Obolellida (Class Calciata, genera *Nochoroiella* and *Obolella*). The former genera had their first occurrences in the *regularis* Zone, whereas the latter appeared in the *lenaicus* Zone of the *Tommotian Stage*. In the second half of the Tommotian time, the genus *Cryptotreta* penetrated into Scandinavia. In the first half of the *Atdabanian Age*, obolellids still inhabited only the Siberian platform in association with the earliest articulates of the Nisusiidae Family. By the mid-Atdabanian time, paterinids dispersed widely over the Anabar–Sinskoe facial region of the Siberian platform, and penetrated into the Altai–Sayan region. *Aldanotreta* is known from southern China and Great Britain, and *Cryptotreta* from Scandinavia. The mid-Atdabanian time known as the starting point of the most extensive Early Cambrian sea transgression (Rozanov, 1984) was marked by rapid distribution and diversification of brachiopods (Figs. 1, 2). In the Siberian platform, Altai–Sayan foldbelt, Mongolia, and Transbaikal region, obolellids increased in abundance and included several newly appeared genera (*Sibiria, Monoconvexa, Magnicanalis, Bicia*). In the middle course of the Lena River, the *Pagetiellus anabarus* and *Judomia* zones contain lentils (0.5–1 cm thick and few meters long) that are composed of separated *Obolella* valves. In the Transbaikal region, the Georgievka Formation of the topmost Atdabanian–basal Botomian includes accumulations of the *Monoconvexa* shells, the former coquina pavements. At the same time (the second half of the Atdabanian) the genus *Obolella* penetrated into North America to give rise to the genus *Alisina*, and the earliest obolellids appeared in North Africa. Brachiopods of the Nisusiidae Family were widespread in the terminal

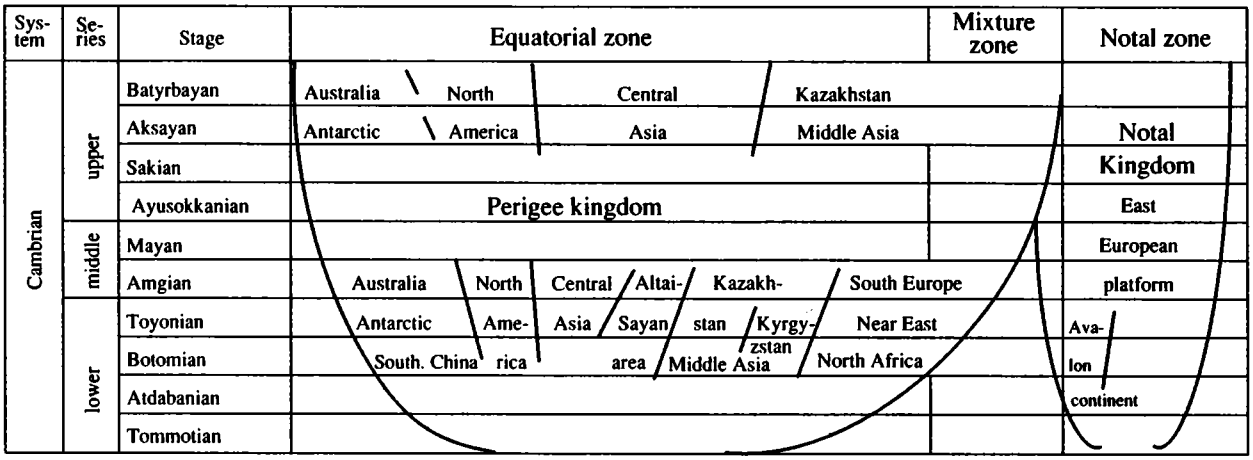

Fig. 2. Development of the Cambrian brachiopod biochores.

Atdabanian. In addition to the Siberian platform, they are recorded in the Altai–Sayan foldbelt, western North America, and Mexico. The Atdabanian obolellids and nususiids are confined to carbonate and clayey-carbonate sediments of the equatorial shallow basins.

In the first half of the Atdabanian, paterinids penetrated into the Avalon continent comprising the British Isles, Newfoundland, Cape David, and the easternmost part of North America (Landing, 1996). Likely, they gave rise to the genera *Paterina* and *Micromitra*, which spread into the East European platform and the Pyrenean Peninsula in the second half of the Atdabanian time. At the same time, the phosphate-shelled brachiopods of two new orders Lingulida and Acrotretida appeared. Their earliest forms were found in terrigenous deposits of the East European platform and the former Avalon continent. Lingulids represented by five genera were particularly abundant. The high taxonomic diversity of lingulids suggests their appearance before the late Atdabanian time, and their remains may be expected to occur also in the Tommotian and lower Atdabanian deposits. In the latest Atdabanian, lingulids and acrotretids penetrated into the Siberian platform and North America, where they are also found predominantly in terrigenous sediments.

Slightly more than 20 genera of brachiopods existed in the late Atdabanian, being equally represented by lingulates and calciates. Two extensive kingdoms characterized by different brachiopod assemblages can be outlined for this time (Fig. 2). One Perigean Kingdom comprised the equatorial regions: northern Asia (the Chukchi Land, Siberian platform, Altai–Sayan foldbelt, Mongolia), the greater part of North America, Kazakhstan, Middle Asia, North Africa, Near East, southern and partly northern China, India, Australia, and the Antarctic. Carbonate and terrigenous-carbonate sediments were predominant in these areas. Dominant among brachiopods were Calciata forms, such as Obolellida and earliest Articulata. Paterinids represented the prevailing group of the phosphate-shelled brachiopods. Lingulids and acrotretids gradually migrated from the high latitudes into the equatorial zone in the latest Atdabanian time. Another, Notal Kingdom was located in the high latitudes of the southern hemisphere and comprised territories of the North and East Europe (East European platform), Avalon continent, and South Europe (a part). Mainly terrigenous deposits of the kingdom contain only lingulates: paterinids, lingulids, and acrotretids.

The next **Botomian Age** was a time of maximum development of the sea transgression that commenced in the mid-Atdabanian. The transgression resulted in wide distribution of carbonate and terrigenous-carbonate facies, and in further dispersal of brachiopods. The brachiopod-bearing Botomian deposits are known in the western and eastern North America, Siberian platform, Altai–Sayan foldbelt, Mongolia, Transbaikal region, Kazakhstan, Middle Asia, North Africa, South Europe, Near East, and southern Australia (table). Each of these regions had their peculiar forms, although some genera occurred in most of them. In the Botomian time, for instance, the vast Perigean Kingdom comprised several large regions or provinces with different brachiopod assemblages (Fig. 2). The provinces were incompletely isolated from each other, as it is evident from some generic affinities, but they hosted specific assemblages of carbonate-shelled brachiopods. So, the Central Asiatic province that included the Siberian platform, Altai–Sayan foldbelt, Transbaikal region, Mongolia, and Far East was a habitat of highly diverse obolellids inherited from the Atdabanian time and associated with abundant *Kutorgina* in the boundary region between the transitional and lagoonal facies zones of the Siberian platform. In both western and eastern parts of North America, there occurred articulates of the genera *Swantonia* and *Eoconcha* in association with kutorginids of the genus *Yorkia*, all unknown outside this area. Like in Siberia, the brachiopod assemblages

Stratigraphic and geographic ranges of the Cambrian brachiopods

Stage	Tommotian				Atdabanian				Botomian				Toyonian			Amgian				Mayan			Ayusokkanian		Sakian			Aksayan		Batyrbayan		Region	Reference
Zone	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	1	2	3	4	1	2	3	1	2	1	2	3	1	2	1	2		
Class LINGULATA **Order Paterinida** Fam. Cryptotretidae																																	
Aldanotreta Pelman, 1979																																Siberian platform	Pel'man, 1977
																																Altai-Sayan foldbelt	Pel'man *et al.*, 1992
				?																												Southern China	Liu Dy-yong, 1979
				?																												Great Britain	Williams *et al.*, 1998
Cryptotreta Pelman, 1979																																Siberian platform	Pel'man, 1977
																																Scandinavia	Williams *et al.*, 1998
																																Altai-Sayan foldbelt	Pel'man *et al.*, 1992
Dzunarzina Ushat., 1993																																Mongolia	Ushatinskaya, 1993
Salanygolina Ushat., 1987																																Mongolia	Ushatinskaya, 1987
Askepasma Laurie, 1986																																Australia	Laurie, 1986
Fam. Paterinidae																																	
Paterina Beecher, 1891																																Spain	Linan, Mergl, 1982
																																Eastern North America	Landing, 1991
																																East European platform	Goryanskii, 1969
																																Great Britain	Hinz, 1987
																																Canada, Mackenzie	Voronova *et al.*, 1987
																																Canada, Labrador	Williams *et al.*, 1998
																																France, Montagne Noir	Kerber, 1988
																																Kazakhstan	Pel'man *et al.*, 1992
																																Altai-Sayan foldbelt	Pel'man *et al.*, 1992
																																Mexico	Stewart *et al.*, 1984
																																Siberian platform	Pel'man *et al.*, 1992
																																Middle Asia	Imanaliev and Pel'man, 1988
																																North America, Texas	Palmer, 1954
Micromitra Meek, 1873																																Eastern North America	Landing, 1991
																																Poland	Jendryka-Fuglewicz, 1992
																																Altai-Sayan foldbelt	Aksarina and Pel'man, 1978
																																Canada, Mackenzie	Voronova *et al.*, 1987
																																Scandinavia	Williams *et al.*, 1998
																																Middle Asia	Imanaliev and Pel'man, 1988
																																Spain	Mergl, Linan, 1986
																																Eastern North America	Walcott, 1912
																																Australia	Roberts, Jell, 1990
																																Mexico	Stewart *et al.*, 1984
																																Argentina	Williams *et al.*, 1998
																																North America, Montana, Utah	Bell, 1941
																																Turkey	Williams *et al.*, 1998
																																Far East	Pel'man *et al.*, 1992
																																Kazakhstan	Pel'man *et al.*, 1992
Dictyonina Cooper, 1942																																North America, Nevada, Texas	Palmer, 1954; Rowell, 1980
																																Australia	Roberts, Jell, 1990
																																Middle Asia	Repina *et al.*, 1975
																																British Columbia	Williams *et al.*, 1998
																																Mexico	Stewart *et al.*, 1984
																																Altai-Sayan foldbelt	Aksarina and Pel'man, 1978
																																Kazakhstan	Koneva, 1986 (2)
																																Far East	Pel'man *et al.*, 1992
																																Scandinavia	Berg-Madsen, 1985
																																Siberian platform	Williams *et al.*, 1998
																																Novaya Zemlya	Popov, 1985
Olenekina Ushat., 1997																																Siberian platform	Ushatinskaya, 1997
																																Greenland	Zell, Rowell, 1988
																																Australia	Engelbretsen, 1996
Inc. Fam.																																	
Bomina Korov. et Ushat., 1994																																Tuva	Ushatinskaya and Korovnikov, 1994
Order Lingulida Fam. Acrothelidae																																	
Acrothele (s. l.) Linnarsson, 1876																																Poland	Jendryka-Fuglewicz, 1992
																																Spain	Linan, Mergl, 1982
																																Iran	Wolfart, 1974
																																Germany	Freyer, 1981
																																North America, Nevada	Rowell, 1980
																																Southern China	Huang *et al.*, 1994
																																Eastern North America	Walcott, 1912
																																Siberian platform	Pel'man *et al.*, 1992
																																South Europe, Montagne Noir	Termier et Termier, 1974
																																Czech Republic	Mergl, Slehoverova, 1990
																																North Africa	Geyer, Landing, 1995
																																Antarctic	Popov and Solov'ev, 1981
																																Altai-Sayan foldbelt	Aksarina and Pel'man, 1978
																																Scandinavia	Puura, Holmer, 1993
																																Kazakhstan	Koneva, 1986 (2)
																																Australia	Henderson, MacKinnon, 1981
																																Middle Asia	Repina *et al.*, 1975
																																North America, Montana, Utah	Bell, 1941
																																Novaya Zemlya	Popov, 1985
																																Far East	Pel'man *et al.*, 1992
Schizopholis Waagen, 1885																																Pakistan	Schindewolf, Seilacher, 1955
																																Kazakhstan	Koneva, 1979

Table. (Contd.)

Stage	Tommotian				Atdabanian				Botomian				Toyonian			Amgian				Mayan			Ayusokkanian		Sakian			Aksayan		Batyrbayan		Region	Reference
Zone	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	1	2	3	4	1	2	3	1	2	1	2	3	1	2	1	2		
Spinulothele Rowell, 1977																																Nevada	Rowell, 1977
Eothele Rowell, 1980																																Canada, Mackenzie	Voronova *et al.*, 1987
																																Australia	Roberts, Jell, 1990
																																Altai-Sayan foldbelt	Aksarina and Pel'man, 1978
Karathele Koneva, 1977																																Australia	Kruse, 1990
																																Antarctic	Holmer *et al.*, 1996
																																Kazakhstan	Koneva, 1986
Orbithele Sdzuy, 1955																																Greenland	Zell, Rowell, 1988
Fam. Botsfordiidae																																	
Botsfordia Matthew, 1891																																Poland	Jendryka-Fuglewicz, 1992
																																Siberian platform	Pel'man, 1977
																																Southern China	Luo *et al.*, 1984
																																North America	Lochman, 1956
																																Canada, Labrador	Walcott, 1912
																																Kazakhstan	Goryanskii and Koneva, 1983
																																India, Pakistan	Schindewolf, Seilacher, 1955
																																North America, New York	Landing, Bartowski, 1996
																																Spain	Walcott, 1912
																																Altai-Sayan foldbelt	Aksarina and Pel'man, 1978
																																Czech Republic	Mergl, Slehoverova, 1990
																																North America	Mergl, 1988
Edreja Koneva, 1979																																Australia	Laurie, 1986
																																Kazakhstan	Koneva, 1979
Neobolus Waagen, 1885																																Pakistan	Schindewolf, Seilacher, 1955
																																Germany	Freyer, 1981
Canalilatus Pelman, 1983 = *Pelmania* Koneva, 1992																																Kazakhstan	Pel'man *et al.*, 1992
																																Siberian platform	Pel'man *et al.*, 1992
Fam. Obolidae																																	
Eobolus Matthew, 1902																																Siberian platform	Ushatinskaya, 1993
																																North America, Massachusetts	Landing, 1988
																																Australia	Ushatinskaya, unpublished
																																Newfoundland	Landing *et al.*, 1988
																																Great Britain	Hinz, 1987
																																Antarctic	Holmer *et al.*, 1996
																																Canada, Cape Breton	Walcott, 1912
																																East European platform	*Opornye...*, 1989
Palaeoshmidtites Koneva, 1979																																Canada, Mackenzie	Voronova *et al.*, 1987
																																Kazakhstan	Koneva, 1979
Lingulepis Hall, 1863																																East European platform	*Stratigrafiya*..., 1979
																																South Europe	Termier et Termier, 1974
																																Eastern North America	Shaw, 1966
Paleobolus Matthew, 1899																																Kazakhstan	Goryanskii and Koneva, 1983
																																North America, New-Brunswick	Walcott, 1912
Lindineiia Mergl, 1990																																Czech Republic	Mergl, Slehoverova, 1990
Obolus Eichwald, 1829																																East European platform	Khazanovich *et al.*, 1984
Notiobolus Popov, 1982																																Antarctic	Popov and Solov'ev, 1981
Oepikites Popov et Khaz., 1987																																East European platform	Khazanovich *et al.*, 1984
																																Altai-Sayan foldbelt	Aksarina and Pel'man, 1978
																																Siberian platform	Ushatinskaya, coll.
																																North America, Texas	Palmer, 1954
Synaglossa Mei, 1993																																Northern China	Mei, 1993
Dicellomus Hall, 1871																																North America, Montana	Bell, 1941
Ungula Pander, 1830																																East European platform	Popov and Khazanovich, 1989
																																Scandinavia	Puura, Holmer, 1993
Rebrovia Popov, Khaz., 1989																																East European platform	*Opornye...*, 1989
Ralfia Popov, Khaz., 1989																																East European platform	*Opornye...*, 1989
Eucbolus Mickwitz, 1896																																East European platform	*Opornye...*, 1989
Schmidtites Schuch., LeVene, 1929																																East European platform	*Opornye...*, 1989
																																Scandinavia	Puura, Holmer, 1993
Fam. Lingulellotretidae																																	
Lingulellotreta Koneva, 1983																																Kazakhstan	Goryanskii and Koneva, 1983
																																Southern China	Jin Yugan *et al.*, 1993
Vaculina Koneva, 1992																																Kazakhstan	Pel'man *et al.*, 1992
Aboriginella Koneva, 1983																																Kazakhstan	Koneva and Popov, 1983
Mirilingula Popov, 1983																																Kazakhstan	Koneva and Popov, 1983
Fam. Dysoristidae																																	
Dysoristus Bell, 1941																																Siberian platform	Pel'man *et al.*, 1992
																																North America, Texas, Montana	Palmer, 1954; Rowell, 1966
																																Kazakhstan	Pel'man *et al.*, 1992
Ferrobolus Havlíček, 1982																																Kazakhstan	Popov, Holmer, 1994
Fam. Kyrshabaktellidae																																	
Kyrshabaktella Koneva, 1986																																North and South Australia	Kruse, 1990; Engelbretsen, 1996
																																Kazakhstan	Koneva, 1986 (2)
																																Siberian platform	Ushatinskaya, coll.
																																Middle Asia	Popov, unpublished
																																Altai-Sayan foldbelt	Pel'man *et al.*, 1992
Fam. Zhanatellidae																																	
Aksarituia Koneva, 1992																																Kazakhstan	Pel'man *et al.*, 1992
Fossuliella Popov, Ushat., 1992																																Kazakhstan	Popov, Holmer, 1994
																																Siberian platform	Ushatinskaya, 1997
Zhanatella Koneva, 1986																																Siberian platform	Ushatinskaya, coll.
																																? Australia, Antarctic	Henderson *et al.*, 1992
																																Kazakhstan	Popov, Holmer, 1994
Koneviella Ushat., 1997																																Siberian platform	Ushatinskaya, 1997

Table. (Contd.)

Stage	Tommotian				Atdabanian				Botomian				Toyonian			Amgian				Mayan			Ayusokkanian		Sakian			Aksayan		Batyrbayan		Region	Reference
Zone	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	1	2	3	4	1	2	3	1	2	1	2	3	1	2	1	2		
Tropidoglossa Rowell, 1966																																North America, Utah	Rowell, 1966
Fam. Experilingulidae																																	
Chakassilingula Ushat., 1992																																Altai-Sayan foldbelt	Pel'man *et al.*, 1992
Experilingula Koneva, Popov, 1983																																Kazakhstan	Koneva and Popov, 1983
Fam. Elkaniidae																																	
Broeggeria Walcott, 1902																																Kazakhstan	Popov, Holmer, 1994
																																Scandinavia	Popov, Holmer, 1994
Elkania Ford, 1886																																North America, Nevada	Moore (ed), 1965
Pseudodicellomus Bell, 1962																																North America, Texas	Bell, Ellingwood, 1962
"Lingulella" s. l.																																Cosmopolite	
"Obolus" s. l.																																Cosmopolite	
"Westonia" s. l.																																Cosmopolite	
Order Acrotretida																																	
Inc. Fam.																																	
Diandongia Rong, 1974																																India	Kumar *et al.*, 1983
																																Southern China	Yin Jicheng, 1980
F. Linnarssoniidae																																	
Linnarssonia Walcott, 1892																																Great Britain	Hinz, 1987
																																Siberian platform	Pel'man, 1977
																																Poland	Yendryka-Fuglewicz, 1992
																																Middle Asia	Imanaliev and Pel'man, 1988
																																Germany	Freyer, 1981
																																Kazakhstan	Goryanskii and Koneva, 1983
																																Canada, Mackenzie	Voronova *et al.*, 1987
																																Altai-Sayan foldbelt	Pel'man *et al.*, 1992
																																Southern China	Huang *et al.*, 1994
																																North America, Utah	Rowell, 1966
																																Antarctic	Popov and Solov'ev, 1981
																																Australia	Henderson, MacKinnon, 1981
																																Mexico	Stewart *et al.*, 1984
																																Гренландия	Zell, Rowell, 1988
																																Far East	Pel'man *et al.*, 1992
Prototreta Bell, 1938																																Kazakhstan	Koneva, 1979, Ushatinskaya, 1986
																																Germany	Freyer, 1981
																																Greenland	Zell, Rowell, 1988
																																Novaya Zemlya	Popov, 1985
																																North America, Utah, Montana	Bell, 1941
																																Altai-Sayan foldbelt	Aksarina and Pel'man, 1978
																																Antarctic	Shergold *et al.*, 1976
Homotreta Bell, 1941																																Siberian platform	Pel'man *et al.*, 1992
																																Kyrgyzstan	Imanaliev, 1983
																																Altai-Sayan foldbelt	Pel'man *et al.*, 1992
																																North America, Montana, Utah	Bell, 1941
Hadroreta Rowell, 1966																																North America, Nevada	Rowell, 1966, 1980
																																Novaya Zemlya	Popov, 1985
																																Middle Asia	Repina *et al.*, 1975
																																Kazakhstan	Ushatinskaya *et al.*, 1986
																																Far East	Pel'man *et al.*, 1992
Vandalotreta Mergl, 1988																																Australia, Antarctic	Holmer *et al.*, 1996
																																Scandinavia	Holmer *et al.*, 1996
																																North Africa	Mergl, 1988
																																Czech Republic	Mergl, 1988
Kostjubella Pop., Holm., Gor., 1996																																Kazakhstan	Popov *et al.*, 1996
Aphelotreta Rowell, 1980																																North America, Nevada	Rowell, 1980
																																Siberian platform	Ushatinskaya, 1994
																																Far East	Pel'man *et al.*, 1992
Anelotreta Pelman, 1986																																Siberian platform	Pel'man *et al.*, 1992
Fam. Acrotretidae																																	
Acrothyra Matthew, 1901																																North America, Nevada	Rowell, 1980
																																North America, Ohio	Rowell, 1966
																																Altai-Sayan foldbelt	Aksarina and Pel'man, 1978
																																Novaya Zemlya	Popov, 1985
Stilpnotreta Henderson, MacKinnon, 1981																																Kazakhstan	Popov *et al.*, 1996
																																Siberian platform	Ushatinskaya, 1994
																																Scandinavia	Puura, Holmer, 1993
																																Australia	Henderson, MacKinnon, 1981
Odontotreta Ushat., 1998																																Kazakhstan	Ushatinskaya, 1998
Mixotreta Ushat., 1998																																Siberian platform	Ushatinskaya, 1998
Amictocraceus Hend. MacKin., 1981																																Australia	Henderson, MacKinnon, 1981
																																Northern China	Mei, 1993
Picnotreta Hend. MacKin., 1981																																Greenland	Zell, Rowell, 1988
																																Kazakhstan	Ushatinskaya, coll.
																																Australia	Henderson, MacKinnon, 1981
Angulotreta Palmer, 1954 = *Treptotreta* Hend., MacKin., 1981																																Australia	Henderson, MacKinnon, 1981
																																Northern China	Mei, 1993
																																North America, Texas, Montana	Palmer, 1954; Grant, 1965
																																Antarctic	Henderson *et al.*, 1992
																																Scandinavia	Puura, Holmer, 1993
																																Siberian platform	Ushatinskaya, 1994
																																Novaya Zemlya	Popov, 1985
																																Kazakhstan	Koneva *et al.*, 1990
																																East European platform	*Opornye*.... 1989
Dicondylotreta Mei, 1993																																Northern China	Mei, 1993

Table. (Contd.)

Stage	Tommotian				Atdabanian				Botomian				Toyonian			Amgian				Mayan			Ayusokkanian		Sakian			Aksayan		Batyrbayan		Region	Reference
Zone	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	1	2	3	4	1	2	3	1	2	1	2	3	1	2	1	2		
Opistotreta Palmer, 1954																																Siberian platform	Pel'man *et al.*, 1992
																																Northern China	Mei, 1993
																																North America, Texas	Palmer, 1954
																																Far East	Pel'man *et al.*, 1992
Neotreta Sobolev, 1976																																Kazakhstan	Popov *et al.*, 1994
																																Australia	Engelbretsen, 1996
																																Great Britain	Popov *et al.*, 1994
																																Middle Asia	Popov *et al.*, 1994
																																Far East	Pel'man *et al.*, 1992
																																Northern China	Mei, 1993
Dactylotreta Rowell, *Henderson*, 1978																																Greenland	Zell, Rowell, 1988
																																Antarctic	Henderson *et al.*, 1992
																																Australia	Rowell, Henderson, 1978
Physotreta Rowell, 1966																																Altai-Sayan foldbelt	Aksarina and Pel'man, 1978
																																North America, Nevada, Utah	Rowell, 1966
Quadrisonia Rowell, *Henderson*, 1978																																Australia	Rowell, Henderson, 1978
																																Antarctic	Henderson *et al.*, 1992
																																Scandinavia	Puura, Holmer, 1993
																																North America, Utah	Rowell, Henderson, 1978
																																Kazakhstan	Koneva *et al.*, 1990
Canthylotreta Row., 1966																																North America, Utah	Rowell, 1966
																																Northern China	Mei, 1993
																																Greenland	Zell, Rowell, 1988
Dicondylotreta Mei, 1993																																North China	Mei, 1993
Apsotreta Palmer, 1954																																North America, Texas, Montana	Palmer, 1954
Linnarssoonella Walcott, 1902																																Dakota, Montana, Texas	Bell, 1941; Rowell, 1966
Olentotreta Kon., Pop., Ushat., 1989																																Kazakhstan	Koneva *et al.*, 1990
Satpakella Kon., Pop., Ushat., 1989																																Kazakhstan	Koneva *et al.*, 1990
Kotujotreta Ushat., 1994 (= *Longipegma* Pop. Holm., 1994)																																Siberian platform	Ushatinskaya, 1994
																																Kazakhstan	Popov, Holmer, 1994
Semitreta Biernat, 1973																																Siberian platform	Ushatinskaya, 1994
																																Poland	Biernat, 1973
Aractina Koneva, 1992																																Kazakhstan	Pel'man *et al.*, 1992
Galinella Holmer, Popov, 1994																																Kazakhstan	Popov, Holmer, 1994
Eurytreta Rowell, 1966																																Kazakhstan	Koneva and Popov, 1988
																																Scandinavia	Popov, Holmer, 1994
Fam. Scaphelasmatidae																																	
Batenevotreta Ushat., 1992																																Altai-Sayan foldbelt	Pel'man *et al.*, 1992
Eoscaphelasma Kon., Pop., Ushat., 1990																																Kazakhstan	Koneva *et al.*, 1990
Tobejalotreta Kon., Pop., Ushat., 1990																																Kazakhstan	Koneva *et al.*, 1990
Fam. Ephippelasmatidae Rowell, 1965																																	
Akmolina Pop., Holm., 1994																																Kazakhstan	Popov, Holmer, 1994
Fam. Anabolotretidae																																	
Kotylotreta Koneva, 1990																																Kazakhstan	Koneva, 1990
Anabolotreta Rowell, *Henderson*, 1978																																Siberian platform	Ushatinskaya, 1994
																																Kazakhstan	Koneva, 1986; Popov *et al.*, 1996
																																Australia	Henderson, MacKinnon, 1981
																																Far East	Pel'man *et al.*, 1992
																																Greenland	Zell, Rowell, 1988
																																Novaya Zemlya	Popov, 1985
																																Northern China	Mei, 1993
Rhondellina Rowell, 1986																																Siberian platform	Ushatinskaya, 1994
																																North America, Utah, Nevada	Rowell, 1986
																																Kazakhstan	Pel'man *et al.*, 1992
																																Greenland	Zell, Rowell, 1988
Anatreta Mei, 1993																																Northern China	Mei, 1993
Fam. Ceratretidae																																	
Kleitriatreta Roberts, Jell, 1990																																Australia	Roberts, Jell, 1990
																																Middle Asia	Popov, unpublished
Bozshakolia Ushat., 1986																																Scandinavia	Henderson, Ushatinskaya, 1992
																																Kazakhstan	Ushatinskaya, 1986
Erbotreta Holm., Ushat., 1992																																Altai-Sayan foldbelt	Henderson, Ushatinskaya, 1992
Ceratreta Bell, 1941																																North America, Montana, Texas	Bell, 1941
																																Far East	Pel'man *et al.*, 1992
																																Scandinavia	Holmer, Popov, 1990
																																East European platform	*Opornye...*, 1989
Keyserlingia Pander, 1861																																East European platform	*Opornye...*, 1989
																																Scandinavia	Puura, Holmer, 1993
Fam. Curticiidae																																	
Curticia Walcott, 1905																																Greenland	Zell, Rowell, 1988
																																North America, Montana, Minnes.	Rowell, Bell, 1961
Inc. fam.																																	
Dzagdicus Sobolev, 1992																																Far East	Pel'man *et al.*, 1992
Order Siphonotretida																																	
Fam. Schizambonidae																																	
Schizambon Walcott, 1884																																Altai-Sayan foldbelt	Aksarina and Pel'man, 1978
																																Antarctic	Shergold *et al.*, 1976
																																North America, Montana	Lochman, 1964
																																Canada	Ulrich, Cooper, 1938
																																East European platform	Puura, 1996
Gorchakovia Pop., Khaz., 1989																																East European platform	*Opornye...*, 1989

Table. (Contd.)

Stage	Tommotian				Atdabanian				Botomian				Toyonian			Amgian				Mayan			Ayusokkanian		Sakian			Aksayan		Batyrbayan		Region	Reference
Zone	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	1	2	3	4	1	2	3	1	2	1	2	3	1	2	1	2		
Class CALCIATA																																	
Order Obolellida																																	
Fam. Obolellidae																																	
Nochoroiella Pel., 1983																																Siberian platform	Pel'man *et al.*, 1992
Obolella Billings, 1861																																Siberian platform	Pel'man, 1977
																																Altai-Sayan foldbelt	Aksarina and Pel'man, 1978
																																North America, Nevada	Rowell, 1977
																																North America, Labrador	Rowell, 1962
																																North America, Massachusetts	Landing, 1988
																																India	Triparthi *et al.*, 1984
																																Spain	Linan, Mergl, 1982
																																Newfoundland	Landing *et al.*, 1988
																																Far East	Pel'man *et al.*, 1992
																																Kazakhstan	Goryanskii and Koneva, 1983
																																East European platform	*Stratigrafiya....* 1979
																																Germany	Freyer, 1981
Monoconvexa Pel., 1977																																Siberian platform	Pel'man, 1977
Sibiria Gor., 1977																																Siberian platform	Goryanskii, 1977
Alisina Rowell, 1962																																Mexico	Stewart *et al.*, 1984
																																Newfoundland	Rowell, 1962
																																Kazakhstan	Koneva, 1979
																																Siberian platform	Pel'man *et al.*, 1992
																																Altai-Sayan foldbelt	Aksarina and Pel'man, 1978
Magnicanalis Rowell, 1962																																Transbaikal region	Ushatinskaya, 1987
																																India	Triparthi *et al.*, 1984
																																Scandinavia	Rowell, 1962
Bicia Walcott, 1901																																Transbaikal region	Ushatinskaya, 1987
																																North America, New York	Rowell, 1962
Brevipelta Geyer, 1994																																North Africa	Geyer, 1994
Ivshinella Koneva, 1979																																Kazakhstan	Koneva, 1979
Trematobolus Matthew, 1893																																Near East	Cooper, 1976
																																North Africa	Geyer, 1995
																																North America, New-Brunswick	Rowell, 1962
																																Siberian platform	Goryanskii *et al.*, 1964
																																Spain	Mergl, Linan, 1986
Order Kutorginida																																	
Fam. Kutorginidae																																	
Khasagtina Ushat., 1988																																Mongolia	Ushatinskaya, 1988
																																France, Montagne Noir	Kerber, 1988
Kutorgina Billings, 1861																																Germany	Freyer, 1981
																																North America, Nevada	Rowell, 1977
																																Altai-Sayan foldbelt	Pel'man *et al.*, 1992
																																Kazakhstan	Koneva, 1979
																																Western North America	Lochman, 1956
																																Siberian platform	Goryanskii *et al.*, 1964
																																Australia	Roberts, Jell, 1990
																																Southern China	Huang *et al.*, 1945
																																Greenland	Popov *et al.*, 1997
Yorkia Walcott, 1897																																North America, New York	Rowell, 1962
																																Altai-Sayan foldbelt	Aksarina and Pel'man, 1978
																																New South Wells	Brock, 1998
																																Spain	Gil Gid, Melou, 1986
Trematosia Cooper, 1976																																Near East	Cooper, 1976
																																Australia	Roberts, Jell, 1990
Agyrekia Koneva, 1979																																Kazakhstan	Koneva, 1979
																																Australia	Laurie, 1986
																																Greenland	Popov *et al.*, 1997
Haupiria MacKinnon, 1983																																Australia	MacKinnon, 1983
Order Naukatida																																	
Bojarinovia Aksarina, 1978																																Altai-Sayan foldbelt	Aksarina and Pel'man, 1978
																																Middle Asia	Popov and Tikhonov, 1990
Naukat Popov, Tikhonov, 1990																																Middle Asia	Popov and Tikhonov, 1990
Oina Popov, Tikhonov, 1990																																Middle Asia	Popov and Tikhonov, 1990
Fam. Pelmanellidae																																	
Pelmanella Pop. Holmer, 1997																																Greenland	Popov *et al.*, 1997
Bynguanoia Roberts, 1990																																Australia	Roberts, Jell, 1990
Order Chileida																																	
Matutella Cooper, 1951																																Siberian platform	Andreeva, 1962
																																North America, Virginia	Cooper, 1951
																																Middle Asia	Andreeva, 1962
																																Altai-Sayan foldbelt	Aksarina and Pel'man, 1978
Kotujella Andreeva, 1962																																Siberian platform	Andreeva, 1962
Chile Popov, Tikhonov, 1992																																Middle Asia	Popov and Tikhonov, 1990
Acareorthis Roberts, Jell, 1990																																Greenland	Popov *et al.*, 1997
																																Australia	Roberts, Jell, 1990
Order Orthida																																	
Fam. Nisusiidae																																	
Nisusia Walcott, 1905																																Siberian platform	Andreeva, 1962
																																North America, Nevada	Rowell, 1977
																																Mexico	Stewart *et al.*, 1984
																																Altai-Sayan foldbelt	Aksarina and Pel'man, 1978

Table. (Contd.)

Stage	Tommotian				Atdabanian				Botomian				Toyonian			Amgian				Mayan			Ayusokkanian		Sakian			Aksayan		Batyrbayan		Region	Reference
Zone	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	1	2	3	4	1	2	3	1	2	1	2	3	1	2	1	2		
																																Eastern North America	Shaw, 1955
																																Kazakhstan	Pel'man *et al.*, 1992
																																Iran	Walfart, 1974
																																Germany	Elicki, 1994
																																Middle Asia	Andreeva, 1962
																																Southern China	Huang *et al.*, 1994
																																Alaska	Cooper, 1936
																																North America, Montana, Utah	Bell, 1941
																																New South Wells	Brock, 1998
																																Australia	Roberts, Jell, 1990
Eoconcha Cooper, 1951																																North America, Virginia	Cooper, 1951
Narimella Andreeva, 1987																																Middle Asia	Andreeva, 1987
Fam. Bohemieillidae																																	
Pompeckium Havliček, 1970																																North America, Nevada	Rowell, 1977
																																Czech Republic	Havliček, 1977
Wimanella Walcott, 1908																																Australia	Kruse, 1990; Roberts, Jell, 1990
																																North America, Montana	Bell, 1941
																																Mexico	Stewart *et al.*, 1984
																																Altai-Sayan foldbelt	Aksarina and Pel'man, 1978
Diraphora Bell, 1941																																Australia	Kruse, 1990
																																Mexico	Stewart *et al.*, 1984
																																North America, Montana	Bell, 1941
																																Altai-Sayan foldbelt	Aksarina and Pel'man, 1978
																																Novaya Zemlya	Popov, 1984
																																North America, Texas	Palmer, 1954
Murrinycella Kruse, 1990																																Australia	Kruse, 1990
Bohemiella Schuchert, Cooper, 1931																																Czechia, Germany	Havliček, 1977
																																New Zealand	MacKinnon, 1983
Oligomys Schuch., Cooper, 1931																																Czech Republic	Havliček, 1977
Brachimorthis Havliček, 1977																																North Africa	Geyer, Mergl, 1997
																																Czech Republic	Havliček, 1977
																																Spain	Havliček, Josopait, 1972
Turarella Andreeva, 1987																																Siberian platform	Andreeva, 1987
Ambardella Andreeva, 1987																																Siberian platform	Andreeva, 1987
Fam. Protorthidae																																	
Glyptoria Cooper, 1976																																Near East	Cooper, 1976
Israelaria Cooper, 1976																																Near East	Cooper, 1976
Psiloria Cooper, 1976																																Near East	Cooper, 1976
Arctohedra Cooper, 1936																																Alaska	Cooper, 1936
																																Australia	Roberts, Jell, 1990
																																Middle Asia	Repina *et al.*, 1975
Jamesella Walcott, 1905																																Spain	Gil Gid, Melou, 1986
																																Western North America	Walcott, 1912
																																Czech Republic	Havliček, 1970
																																North Africa	Geyer, Mergl, 1997
Loperia Walcott, 1905																																Western North America	Walcott, 1912
Saesorthis Geyer, Mergl, 1997																																North Africa	Geyer, Mergl, 1997
Protorthis H. et Cl., 1892																																Eastern North America	Walcott, 1912
Fam. Leioritidae																																	
Leioria Cooper, 1976																																Near East	Cooper, 1976
Fam. Eoorthidae																																	
Swantonia Walcott, 1908																																North America, Nevada	Rowell, 1977
																																North America, Vermont	Shaw, 1962
Wynnia Walcott, 1908																																Pakistan	Schindewolf, Seilacher, 1955
Chilidorthis Havliček, 1972																																Spain	Havliček, Josopait, 1982
Cymbricta Roberts, Jell, 1990																																Australia	Roberts, Jell, 1990
Australohedra Roberts, Jell, 1990																																Australia	Roberts, Jell, 1990
? *Glaphyorthis* Roberts, Jell, 1990																																Australia	Roberts, Jell, 1990
Engenella Andreeva, 1987																																Siberian platform	Andreeva, 1987
Eoorthis Walcott, 1908																																Altai-Sayan foldbelt	Pel'man *et al.*, 1992
																																Scandinavia	Walcott, 1912
																																N. America, Oklahoma, Texas	Freeman, Stitt, 1996
																																Siberian platform	Andreeva, 1968
																																Southern China	Luo, 1984
																																USA, Montana, Texas	Bell, 1941; Bell, Ellinwood, 1962
																																Far East	Pel'man *et al.*, 1992
Oenerorthis Bell, 1941																																Novaya Zemlya	Popov, 1984
																																Siberian platform	Andreeva, 1987
																																North America, Montana	Bell, 1941; Grant, 1965
Otusia Walcott, 1905																																Argentina	Walcott, 1912
																																USA, Oklahoma, Montana	Grant, 1965; Freeman, Stitt, 1996
Bajanorthis Andreeva, 1968																																Siberian platform	Andreeva, 1968
Apheoorthis Ulrich, Cooper, 1936																																Siberian platform	Pel'man *et al.*, 1992
																																Southern China	Luo, 1984
																																North America, Montana	Grant, 1965
																																Kazakhstan	Nikitin and Popov, 1983
Ambardella Andreeva, 1987																																Siberian platform	Andreeva, 1987
Archaeorthis Ulrich, Cooper, 1938																																N. America, Vermont, Nevada	Ulrich, Cooper, 1938
Fam. Finkelnburgiidae																																	
Orusia Walcott, 1905																																Great Britain	Allen *et al.*, 1981
																																Scandinavia	Walcott, 1912
																																Poland	Jendryka-Fuglewitz, 1992
																																Newfoundland	Walcott, 1912
Marsharella Andreeva, 1968																																Siberian platform	Andreeva, 1968

Table. (Contd.)

Stage	Tommotian				Atdabanian				Botomian				Toyonian			Amgian				Mayan			Ayusokkanian		Sakian			Aksayan		Batyrbayan		Region	Reference
Zone	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	1	2	3	4	1	2	3	1	2	1	2	3	1	2	1	2		
Finkelnburgia Walcott, 1905																																N. America, Minnes., Wisconsin	Grant, 1965; Freeman, Stiff, 1996
																																Southern China	Luo, 1984
Fam. Billingsellidae																																	
Billingsella Hall et Cl., 1892																																North Africa	Mergl, 1983
																																Great Britain	Cobbold, 1921
																																Scandinavia	Walcott, 1912
																																North America, Montana, Texas	Freeman, Stiff, 1996
																																Spain	Havliček, Josopait, 1972
																																Altai-Sayan foldbelt	Pel'man *et al.*, 1992
																																Novaya Zemlya	Popov, 1984
																																Iran	Ushatinskaya, coll.
																																Southern China	Luo, 1984
																																Siberian platform	Andreeva, 1968
																																Antarctic	Shergold *et al.*, 1976
																																Kazakhstan	Nikitin and Popov, 1983
Cymbithyris Cooper, 1952																																North America, Oklahoma	Freeman, Stitt, 1996
Kozluchinella Severgina, 1967																																Australia	Laurie, 1997
Order Pentamerida																																	
Tcharella Andreeva, 1987																																Siberian platform	Andreeva, 1987
Cambrotrophia Ulrich, Cooper, 1937																																Siberian platform	Andreeva, 1987
																																Kazakhstan	Nikitin, 1956
																																Australia	Hill, Playford, Woods, 1971
																																North America, Utah	Ulrich, Cooper, 1938
Huenella Walcott, 1912																																Western North America	Shaw, 1966
																																USA, Oklahoma, Montana	Bell, 1941; Freeman, Stitt, 1996
																																Southern China	Luo, 1984
																																Siberian platform	Andreeva, 1968
																																Kazakhstan	Nikitin, 1956
Syntrophia Hall, 1892																																North America, Texas, Utah	Walcott, 1912
																																China	Walcott, 1912
Mogoktella Andreeva, 1968																																Siberian platform	Andreeva, 1968
Bobinella Andreeva, 1968																																Siberian platform	Andreeva, 1968, 1987
Plectotrophia Ulrich, Cooper, 1936																																North America, Texas	Bell, Ellinwood, 1962
Mesonomia Ulr., Cooper, 1936																																Southern China	Luo, 1984
																																Kazakhstan	Nikitin and Popov, 1983
																																Eastern North America	Cooper, 1952
Glyptotrophia Ulrich, Cooper, 1936																																Eastern and western N. America	Ulrich, Cooper, 1938
Clarkella Ulrich, Cooper, 1938																																Eastern and western N. America	Ulrich, Cooper, 1938
Palaeostrophia Ulrich, Cooper, 1931																																Southern China	Luo, 1984
																																Kazakhstan	Nikitin and Popov, 1983
																																Eastern North America	Ulrich, Cooper, 1938
Radkeina Laurie, 1997																																Australia	Laurie, 1997

with abundant and diverse obolellids were widespread in the Kazakhstan–Middle Asiatic province. The assemblages were devoid of *Sibiria, Monoconvexa, Bicia*, and *Magnicanalis* but contained abundant *Ivshinella*. Two kutorginid genera *Kutorgina* and *Agyrekia* were also present in this province.

Inside the provinces we can outline some areas characterized by dominant group of endemic brachiopods. For instance, representatives of archaic, probably aberrant orders Naukatida (genera *Bajarinovia, Oila*, and *Naukat*) and Chileida (genus *Chile*) were peculiar of Kyrgyzstan and some areas of the Kazakhstan–Middle Asiatic province. Genera *Glyptoria, Psiloria, Israelaria*, and *Leioria* of orthids and *Trematosia* of kutorginids are described from the Botomian deposits of Near East (Israel and Jordan) and North Africa, the regions of the Paragondwanan or South European–North African province. These genera are unknown in other areas. Endemism of the listed taxa can be explained either by the geographic isolation and increasing specialization of competing genera (Naimark and Rozanov, 1997), or by the inadequate knowledge on Cambrian brachiopods.

Phosphate-shelled brachiopods were not as restricted regionally as the carbonate-shelled forms probably owing to the Botomian sea transgression and to their biological peculiarities: they spread wider in the pelagic environment and were more adaptable to different biotopes. Of the Botomian brachiopods, paterinids (the genera *Paterina* and *Micromitra*) and lingulids (the genera (*Eoobolus, Lingulella* (s.l.), *Acrothele*, and *Botsfordia*) had the widest distribution. They are present in terrigenous-carbonate sediments but absent from pure limestones. The acrotretid genus *Linnarssonia* that probably gave rise to the close genera *Homotreta, Hadrotreta* and later *Vandalotreta* is known from many regions. A peculiar brachiopod assemblage characterizes southern Australia. The Class Calciata is represented by presumable kutorginids (genus *Agyrekia*), and the Class Lingulata includes *Askepasma* and *Eoobolus* occurring in other regions, earliest forms of *Kyrshabaktella* similar to the North American *Dicellomus*, and endemic representatives of the Botsfordiidae Family. This region is recognized as the Australian province.

In South China that was also situated to the equatorial zone, scarce Botomian brachiopods are found in fine-grained terrigenous deposits of the Qiongzhussi Formation. The specimens found are representatives of the widespread genera *Botsfordia, Paterina*, and *Lingulellotreta*. Probably, they inhabited a deeper shelf zone and can be hardly compared therefore with the assemblages of shallow-water carbonate biotopes of other areas of the equatorial zone (Chen *et al.*, 1989). For this reason, the South China territory has not been distinguished as an independent biogeographic unit.

The Notal Kingdom including the East European platform and the Avalon continent was positioned in the higher latitudes of the southern hemisphere. It was characterized by predominantly terrigenous sedimentation. Single carbonate-shelled brachiopods were only found in the western and northern parts of the East European platform. On the contrary, phosphate-shelled brachiopods were found in many sections. They are represented by genera of all three Early Cambrian orders: *Paterina, Micromitra, Botsfordia*, earliest *Lingulella* (s.l.), *Acrothele* (s.l.), and *Acrotreta* (s.l.). In the Botomian time, these taxa composed a dominant group of the Notal Kingdom, and most of them also occurred in other regions. The marginal Avalon continent was adjacent to the low latitudes and represented an independent province characterized by mixed fauna. Predominantly terrigenous deposits of the continent include limestone interbeds, where phosphate-shelled brachiopods are associated with obolellids.

In the **Toyonian time** the distribution areas of brachiopods became reduced. Their remains are extremely rare in Kazakhstan, Central Asia, southern China, and Near East, and few finds are known from North Africa and South Europe. In the isolated Central Asiatic province, the Toyonian brachiopods occurred in the Siberian platform and the Altai–Sayan foldbelt (table). In this province, the carbonate-shelled brachiopods remained still dominant, and surviving obolellids and kutorginids (*Obolella, Sibiria, Alisina, Trematobolus*, and *Kutorgina*) coexisted with articulates known from older deposits and representing newly appeared genera (*Nisusia, Matutella, Kotujella*, and *Tcharella*), distribution areas of which progressively grew. In contrast, the phosphate-shelled brachiopods represented the long-lived genera *Eoobolus, Botsfordia, Linnarssonia*, and *Homotreta*. There could be connections between the North American and Australian provinces, as it is evident from migration of genera *Paterina, Micromitra*, and *Eothele* in Australia. However, the Australian basin retained its specific features, because the brachiopod assemblage of new orthid genera *Wimanella, Diraphora*, and *Murrinyella* appeared there. The Antarctic Toyonian brachiopod assemblage did not differ from the Australian one in composition (Holmer *et al.*, 1996).

The East European platform was still a part of the Notal Kingdom. Sedimentation areas noticeably reduced here by the end of the Botomian. The Toyonian marine terrigenous deposits occur only in the Baltic syneclise, Podlyaska–Brest depression, and the Lyubel' slope (Mens *et al.*, 1987). They contain the uniform assemblage of phosphate-shelled *Botsfordia*, acrotretids similar to *Linnarssonia*, and lingulids *Lingulella* (s.l.).

The Amgian time of the initial Middle Cambrian was characterized in the equatorial zone by the increased abundance of brachiopods and their mass accumulations. The Order Acrotretida was especially diverse. Many genera of both lingulates and calciates had worldwide distribution. However, there were still regional differences in dominating genera (table, Figs. 1, 2).

As in the Early Cambrian, there was the Central Asiatic province comprising the Siberian platform, Altai–Sayan foldbelt, Mongolia, Far East, and Transbaikal region. In the Siberian platform, brachiopod fauna inhabited the basins inherited from the Early Cambrian. All Toyonian genera of the phosphate-shelled brachiopods survived and coexisted with newcomers *Kyrshabaktella* and *Oepikites*, which migrated respectively from Australia and probably the East European platform of the Notal Kingdom. Calciates were represented by the latest obolellids (*Trematobolus*), abundant *Nisusia* and *Matutella*, and by *Cambrotrophia* genus of second Cambrian order Pentamerida. In the Far East and Mongolia, an impoverished brachiopod assemblage included *Lingulella* (s.l.), *Botsfordia*, and acrotretids unidentified at the generic level. In the Altai–Sayan foldbelt, dominating components of the brachiopod association were lingulates represented by genera known in the Siberian platform (*Oepikites, Kyrshabaktella, Linnarssonia, Prototreta*, and *Homotreta*) and by those migrated from other areas (*Eothele* and *Dictyonina*). In addition, there appeared genera of the families Scaphelasmatidae (*Batenevotreta*) and Experilingulidae (*Chakassilingula*) in association with the earliest genus *Erbotreta* of Ceratretidae. As in the Siberian platform, calciates were represented there by *Nisusia* and *Matutella*. The Altai–Sayan foldbelt of the Amgian time could be the secondary diversification center of the phosphate-shelled brachiopods in the marginal zone of the Central Asiatic province.

The Kazakhstan–Central Asiatic province was another secondary center of diversification of phosphate-shelled brachiopods. There appeared some new genera of the Order Acrotretida (*Neotreta, Stilpnotreta, Anabolotreta*, and *Kotylotreta*), which spread globally later on. They associated with *Paterina, Dictyonina*, and *Kyrshabaktella*, which probably migrated from the Central Asiatic province. The carbonate-shelled brachiopods were represented by the Early Cambrian genera *Wimanella, Diraphora*, and *Cambrotrophia* widespread in the Middle Cambrian, and by *Arctohedra* known from Alaska (Pel'man *et al.*, 1992).

In the North American province, the Early Cambrian genera *Micromitra, Dictyonina, Lingulella* (s.l.), *Eoobolus, Acrothele, Linnarssonia, Prototreta, Homotreta*, and *Hadrotreta* were still dominant among the phosphate-shelled brachiopods. The single newcomer was genus *Aphelotreta*. Assemblages of carbonate-shelled brachiopods consisted of the widespread genera *Nisusia, Wimanella, Diraphora, Jamesella*, and *Cambrotrophia*, and of the newly appeared genera *Loperia* and *Protorthis*. Supposedly, the North American basin was on the way of brachiopod migration from the Australian province into the Central Asiatic and Kazakhstan–Central Asiatic provinces.

The Australian province was still distinct owing to a very peculiar brachiopod association. The very diverse assemblage of carbonate-shelled brachiopods consisted here of the widespread *Nisusia, Wimanella, Arctohedra, Acareorthis*, and *Cambrotrophia*, and of newly appeared *Cymbricia, Australohedra*, and *Glaphyorthis* by The Early Cambrian *Eoobolus, Kyrshabaktella, Linnarssonia, Prototreta, Paterina, Micromitra, Acrothele*, and *Vandalotreta* were dominated among the phosphate-shelled brachiopods and associated with newly appeared *Amictocracens, Picnotreta*, and *Angulotreta.*

In the initial Middle Cambrian, the South European–North African (Paragondwanan) province was likely located in the marginal part of the Perigean Kingdom, close to the Notal one, and could represent a zone of mixing of the Equatorial and Notal faunas (Fig. 2). Main components of brachiopod assemblages were the phosphate-shelled forms representing the widespread genera *Paterina, Micromitra, Acrothele, Botsfordia*, and *Vandalotreta.* Calciates consisted of some endemic genera (*Bohemiella, Brachimorthis*, and *Chilidorthis*), surviving obolellids (*Trematobolus, Yorkia*), and *Jamesella* known from other areas as well.

Brachiopod assemblages of the Notal Kingdom are found only in the East European platform, where they were still dominated by phosphate-shelled brachiopods of a poor generic composition. Lingulates included *Lingulella* (s.l.), *Oepikites, Westonia, Acrothele*, and *Botsfordia.* The associated *Bozshakolia* and *Hadrotreta* are known from the northern Scandinavia and Novaya Zemlya Archipelago, respectively.

In the Mayan time of the Middle Cambrian and the Ayusokkanian time of the Late Cambrian, the brachiopod assemblages of the Perigean Kingdom became surprisingly uniform, and their provincial differentiation is hardly noticeable (Fig. 2). Predominant elements were lingulates of a greatly increased diversity. The radiation of the Orders Lingulida and Acrotretida was especially noticeable. A number of Calciata genera diminished significantly (Fig. 1), probably, due to reduction of shallow shelf areas. Lingulates could occupy the relatively deep biotopes with silty substrates in the outer shelves. The corresponding lingulate assemblages are widespread in the northern Siberian platform, Greenland, Malyi Karatau Ridge, and North China (Ushatinskaya, 1994; Pel'man *et al.*, 1992; Zell and Rowell, 1988; Mei, 1993). The assemblages usually dominated by acrotretids are highly diverse (7–10 genera), rich in taxa of a wide geographic distribution. Genera *Paterina, Acrothele, Linnarssonia*, and *Homotreta*, which originated in the Early Cambrian, and *Stilpnotreta, Angulotreta, Anabolotreta*, and *Dactylotreta* of the middle Middle Cambrian origin dispersed almost over the entire globe. In addition to genera, some their species were also widespread.

Sediments predominant in the Notal Kingdom, the East European platform included, were the uniform quartz sands. Their brachiopod assemblages are almost invariable in composition and consist of dominant lingulid genera *Obolus* and *Oepikites* that associated with less frequent *Botsfordia, Acrothele*, and paterinids. Only in the northernmost Scandinavia and Novaya Zemlya Archipelago, which were probably located close to the low latitudes, thin limestone interbeds contain *Stilpnotreta, Angulotreta*, and *Diraphora* characteristic of the equatorial zone.

From the early Sakian till the end of the Cambrian, the Perigean biochores were again differentiated (Fig. 2). In the Siberian platform, Altai–Sayan foldbelt, Transbaikal region, and Mongolia (Central Asiatic province), the phosphate-shelled brachiopods occurred sporadically, but assemblages of the carbonate-shelled forms included frequent representatives of cosmopolitan *Billingsella* and *Eoorthis*, and of newly appeared genera *Ambardella, Bajanorthis, Marsharella, Mogoktella*, and *Bobinella.* In contrast, the phosphate-shelled brachiopods of the Kazakhstan–Central Asiatic province were more diverse than the carbonate-shelled ones. They were represented by some widespread (*Broeggria, Fossuliella*, and *Angulotreta*) and dominant endemic (*Mirilingula, Experilingula, Satpakella, Olentotreta, Akmolina*, and *Eoscaphelasma*) genera unknown outside Kazakhstan. Taxa of the carbonate-shelled brachiopods were the abundant *Billingsella*, rare *Mesonomia* and *Apheorthis* recorded also in North America, and *Huenella* found in North America and Siberian platform. So, the Kazakhstan–Central Asiatic province could be a place of origination of some phyletic lines of phosphate-shelled brachiopods that evolved in the Early Ordovician.

On the contrary, the North American province hosted the highly diverse carbonate-shelled brachiopods and an impoverished assemblage of lingulates. In addition to the mentioned *Billingsella, Mesonomia*, and *Huenella*, the carbonate-shelled taxa were genera *Cymbrithyris, Archaeorthus, Syntrophia, Plectotrophia, Glyptotrophia, Clarkella*, and *Palaeostrophia.* Among the phosphate-shelled taxa, there were *Broeggeria, Ceratreta, Dactylotreta*, and *Schizambon* known also from other regions.

No brachiopods of the second half of the Cambrian are known from Australia, Antarctica, northern and

southern China, and India. The reported occurrence of widespread *Dactylotreta, Schizambon, Eoorthis, Billingsella, Syntrophia*, and *Palaeostrophia* may suggest connections between the Antarctic- and Australian–Chinese basin with other seas of the equatorial zone. Characterization of brachiopod from the South Europe, North Africa, and Near East is indefinite. Single forms from these regions mostly belong to the cosmopolitan genus *Billingsella*, and can neither to characterize this region as an independent biochore, nor to unite it with other regions.

As before, the East European platform belonged to the Notal Kingdom. A sea basin of very variable configuration was located in its northwestern part that was an area of terrigenous sedimentation. The brachiopod assemblage was dominated by lingulates. A zone nearest to the basin coast was occupied by the monotypic *Ungula* community. More distant areas were inhabited by the *Oepikites* community, and deepest parts by *Oepikites, Rebrovia, Ceratreta, Keyserlingia*, and *Gorchakovia* (*Opornye...*, 1989). The distribution areas of first two communities are locally characterized by mass accumulations of shells that are known as localities of "Obolidae Sandstone" used to main phosphorite. The *Obolus* and *Oepikites* assemblages also occur in the Moscow syneclise. In northern Poland and Scandinavia located at that time in lower latitudes, deposits of the second half of the Late Cambrian contain accumulations of *Orusia*.

CONCLUSIONS

In the Cambrian Period, like in the later Phanerozoic time, the brachiopod distribution was mostly determined by climatic zoning. There were two, the Equatorial and vast Notal climatic zones, to which the Perigean and Notal brachiopod kingdoms corresponded respectively. Differences in brachiopod assemblages of the kingdoms became pronounced beginning from the second half of the Atdabanian time. During the Cambrian, the most abundant and diverse brachiopods of the Perigean Kingdom were those of the Class Calciata. In the Botomian time, the Perigean Kingdom split up into some water basins that differed in generic composition of the orders Obolellida, Kutorginida, and Orthida in the Early Cambrian and of the orders Orthida and Pentamerida in the Late Cambrian. These relatively insignificant differences presumably indicate the beginning of biogeographic differentiation. However, the Cambrian brachiopod assemblages were so scarce that we can rather speak of brachiopod provinces. In the interval from the Mayan time of the Middle Cambrian till the Ayusokkanian time of the Late Cambrian, the Perigean Kingdom was surprisingly uniform in composition of brachiopods, and its provincial differences cannot be revealed. This kingdom broke up again into a number of biochores in the second half of the Cambrian. The Notal Kingdom represented throughout the Cambrian a single biochore that hosted almost exclusively the brachiopods of the Class Lingulata.

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Regularities in Evolution of Jurassic Foraminifers

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Abstract—The evolution of foraminifers during the Jurassic is considered in two aspects. The evolutionary aspect proper was analyzed using the internal biological features of these organisms and history of this faunal group was analyzed as depending on many factors that determine an intricate multicomponent evolutionary process, i.e., the compositional changes in assemblages, transformations related to habitat factors, spatial dispersion, etc. There are two main types of assemblages that differ in phylogeny and important parameters, such as the evolution rate at the species and generic levels, specialization degree, dominant species morphotypes, dimensions of adaptive areas, tolerance (ecological valence), and community structure with regard to constituent species and genera. The role of ecological factor and its influence on compositional transformation in foraminiferal communities of Jurassic seas in different climatic zones is analyzed.

Key words: evolution, foraminifers, cosmopolites, endemic communities, Jurassic basins, phylogeny.

Investigating any group of fossil organisms that existed during the prolonged period (over 70 m.y. in the case of Jurassic foraminifers) we get a possibility to trace their successive transformation and development, as well as peculiar phylogeny and phylogenetic cycles in separate lineages. Studying at a global scale this fauna from different climatic zones, where it populated various structural–facies and paleolandscape settings, we can observe changes of organisms under the environmental impact. Considering further the spatial variations in communities that occupied different adaptive niches and were characterized by distribution areas different in dimensions and geographical position, we can estimate their adaptive potential and tolerance, and to discriminate groups of different paleogeographic distribution, i.e., those of endemic to cosmopolitan types.

Analyzing all these features, we obtain a possibility to discriminate stages of intense and decelerated faunal transformations, to estimate evolution rates for the different-rank taxa, to define different types of phylogeny in separate groups, and to establish interrelationships between the taxon life span, its adaptive area, evolution rate, and type of phylogeny. In other words, a synthesis of all these data allows us to obtain a general concept of macroevolution of foraminifers that populated Jurassic seas.

Jurassic foraminiferal assemblages are characterized by a high taxonomic diversity and include 17 orders, 243 genera, and over 1000 species (Basov and Kuznetsova, 2000), Composition and proportions of genera and higher-rank taxa substantially varied with time. Trends of these changes are distinctly oriented toward the increase in abundance of all taxa, from species to order. Parallel to the general sinusoid–successive development from the Hettangian to Tithonian, the species abundance in foraminiferal communities increased by a factor exceeding 25, and the abundance of their genera became approximately 12 times higher. The number of orders became almost three times greater. This phenomenon reflects only one aspect of the evolutionary process, and precisely this trend of foraminiferal evolution can be adequately estimated and analyzed.

Significantly less obvious are trends in morphological evolution of the entire Jurassic foraminiferal fauna and even of individual phylogenetic lineages. Simultaneously, precisely the phylogenetic lineages represent the primary objects, the study of which determines an accuracy of further interpretations.

Different aspects of evolution of fossil organisms are discussed in many works, the number of which increased recently. Many of these works consider the problem in the context of general theoretical, most often biological aspects. Amid them, I should mention works by Berg (1922), Simpson (1948), Shmal'gauzen (1968), Krasilov (1973, 1977), Timofeev-Resovskii *et al.* (1973), Meyen (1974), Budyko (1975), Walliser (1984), Ponomarenko and Dmitriev (1993), and by Markov and Neimark (1995, 1998). Significantly less frequent are publications dealing with evolution of foraminifers. Many of them are published by our contemporaries, because this group attracted a particular interest in the middle of the 20th century, when foraminifers were studied in detail for practical purpose during biostratigraphic researches. These abundant materials stimulated an interest to general problems of foraminiferal evolution, which are considered in a series of works (Fursenko, 1950; Loeblich and Tappan, 1964; Solov'eva, 1966; Rauser-Chernousova, 1968; Dolitskaya, 1972; Mikhalevich, 1980; and others).

Evolution of Jurassic foraminifers is analyzed in a few works only (Fursenko, 1958, 1978; Hottinger, 1981; Grigyalis, 1982; Kuznetsova, 1982, 1994, 1998; Septofontaine 1988).

As one can see from above works dedicated to different aspects of foraminiferal evolution, the problem is considered based on materials obtained for different-age and taxonomic groups. Abundant data on Jurassic foraminifers—benthic and planktonic, secretory and agglutinated, primitive and highly specialized, Arctic and tropical—that were collected during several decades provided an opportunity to clarify this problem to some extent.

As Fursenko (1950) noted, the evolution of foraminifers (as well as of any other group of fossil organisms) can be considered in two aspects that require two corresponding approaches:

(1) The general study of development of foraminiferal faunas consisting of different genera and families. It seems reasonable to consider this aspect (Fursenko termed it paleofaunal) as historical–paleofaunal, because it reflects a wide spectrum of temporal and spatial changes in foraminiferal communities. This approach is based on the detailed study of communities as a whole and of their total diversity.

(2) The study of development of different species and higher-rank (genera, families) taxa, considering this process as a result of species changes and their transformations into new species and genera, which differ in morphological features from their predecessors. In opinion of Fursenko, this aspect is evolutionary, or phylogenetic, and should be based on the study of individual phylogenetic lineages in order to define trends of morphological evolution and types of phylogeny. Naturally, evolution in its historical–faunal and phylogenetic aspects is a complex process that includes migration, changes in adaptive areas, influence of global and local geological events responsible for mutation, and homeostasis.

The evolutionary trends of foraminiferal communities in time and space are detectable first of all in their diversity, dynamics of which shows the clear diversification of taxonomical composition in all climatic zones and at all taxonomic levels. Dynamics of this kind reflects a progressive development of this faunal group during the Jurassic and its diversification that was highest in at the end of this period.

The analysis of Jurassic assemblages from the Arctic, Boreal, and Tethyan (Tropical) zoochores revealed substantial differences in their composition and development patterns. The results of the study of some phylogenetic lineages in dominant genera representing three main types of the foraminiferal fauna (Basov, 1974, 1991) showed different phylogenetic development of highly specialized tropical cyclamminid–pfenderinid communities, on the one hand, and cosmopolitan nodosariid–epistominid communities of a high tolerance degree, on the other (Kuznetsova, 1994, 1997, 1998). It seems reasonable to start the analysis of this phenomenon with consideration of particular phylogenetic lineages of both groups.

The well-studied Jurassic foraminiferal fauna of the Boreal zoochore includes groups of species that represent dominant and subdominant genera *Lenticulina, Astacolus, Planularia, Saracenaria, Marginulina, Citharina, Chitharinella*, (order Lagenida), and also *Epistomina, Pseudolamarckina*, and *Mironovella* (order Rotaliida). When studying phylogenetic lineages, it is important to discriminate and determine biozones of every species representing the above genera using the most complete sections within their distribution areas. I consider here the biozone of any taxon (in our case of species) as corresponding to its complete stratigraphic range. The biozone is a main unit of biostratigraphic zonal scales elaborated recently, using Jurassic foraminifers, for most regions of different zoochores of all climatic belts. Sometimes, species biozones in different basins can substantially differ from each other, and summary data on different basins give therefore the most adequate and complete picture. This topic was discussed by Grigyalis (1985) and made it possible to define several genetically related groups of Jurassic species of the *Lenticulina, Epistomina*, and *Pseudolamarckina* genera in the Baltic region.

Earlier, Kuznetsova (1961) defined several Jurassic species of the *Lenticulina* genus (*L. polonica* group) that bear characteristic morphological features in common and allow their development to be traced from the Bajocian to the terminal Jurassic and the trend in morphological evolution of this group to be defined. It should be noted that interpreting phylogenetic relationships between any foraminiferal groups we naturally pay attention to most prominent morphological features. In the *L. polonica* group, these features are surficial ornamentation of the test, interlocular sutures, and peripheral margin. However, precisely these features appeared to be less suitable for tracing evolutionary changes in this group of species. They are distinctive for species but do not permit to outline trends of successive morphological changes with time. More progressive and indicative appeared to be features, which are externally less expressed and poorly observable, e.g., the degree of text convexity (ratio between diameter and thickness) and elongation index (ratio between maximal and minimal diameters). Gradual changes in these features from the Bajocian to Tithonian demonstrate a distinct tendency in the first parameter (d : H) decrease of the second one (D : d), since the Late Jurassic tests became more convex and rounded as compared with those of the Bajocian Stage (Fig. 1). Similar trends were also established in species groups of other nodosariid genera *Saracenaria, Marginulina*, and *Citharinella* (Kuznetsova, 1962, 1965; Kuznetsova and Umanskaya, 1970).

Grigyalis (1982, 1985) who studied in detail the Jurassic representatives of the Ceratobuliminidae and

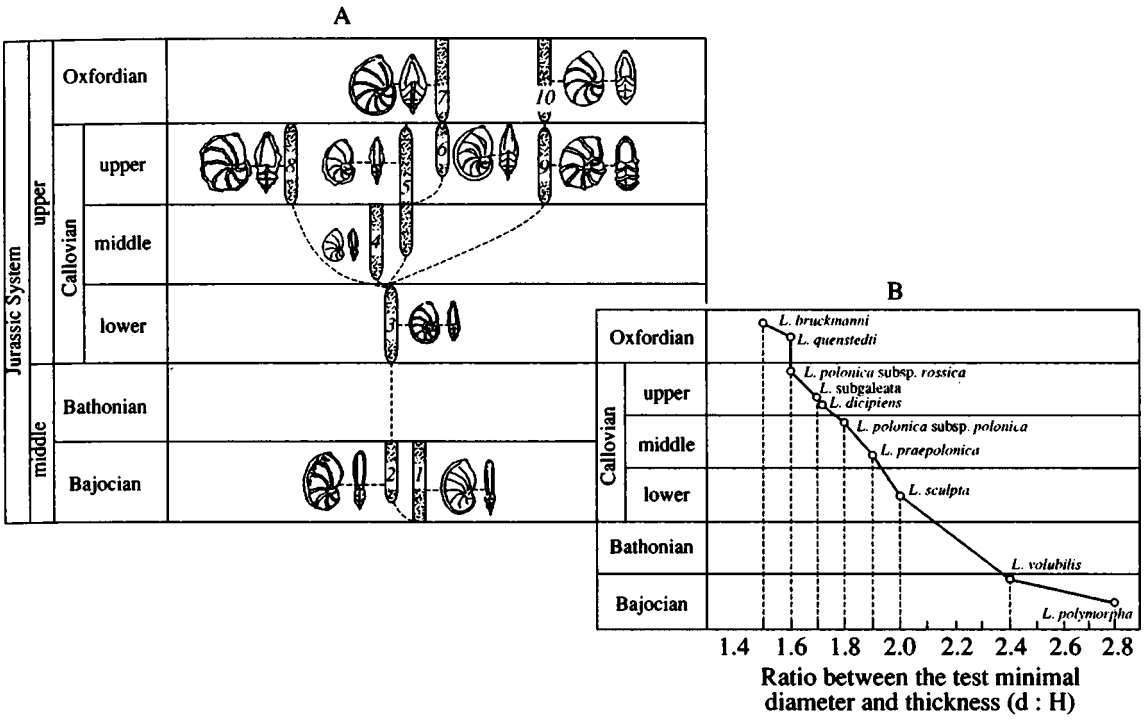

Fig. 1. Development of the *Lenticulina polonica* group in the East European platform during the Jurassic (A) and (B) changes in the test convexity (d/H ratio between the test minimal diameter and thickness) of some species of this group: (*1*) *Lenticulina polymorpha* (Terq.); (*2*) *L. volubilis* Dain; (*3*) *L. sculpta* Mitjanina; (*4*) *L. praepolonica* K. Kuzn.; (*5*) *L. polonica* subsp. *polonica* (Wisn.); (*6*) *L. polonica* subsp. *rossica* K. Kuzn.; (*7*) *L. quenstedti* (Gümb.); (*8*) *L. subgaleata* (Wisn.); (*9*) *L. decipiens* (Wisn.); (*10*) *L. brueckmanni* (Mjatl.).

Epistominidae (order Rotaliida) in addition to nodosariids also demonstrated similar development patterns (Fig. 2). It should be noted that during two decades bracketed between publications by Kuznetsova and Grigyalis, many new species, which were established and studied, allowed the last author to interpret more adequately phylogenetic development of some genera, the *Lenticulina* genus included.

The analysis of phylogenetic lineages of Jurassic foraminifers, which represent the above-mentioned families of cosmopolites and semicosmopolites (taxa cosmopolitan outside the Arctic regions) dominant in the Boreal zoochore, shows that these groups had much in common in their development and evolved in line with the so-called "bunch-type" (the term by E.F. Gur'yanova) evolution that is reflected in the simultaneous existence of many species constituting the core of a genus (Kuznetsova, 1994, 1997, 1998). The last feature is particularly well pronounced in phylogenetic lineages within genera *Lenticulina* and *Citharinella*, the latter represented by more than 20 species. It is remarkable (Figs. 3, 4) that 12 of them coexisted in the early Kimmeridgian seas of the Russian platform (Kuznetsova and Umanskaya, 1970). It is noteworthy that the genus *Citharinella* represents a rare exception because, it is a Boreal endemic, whereas *Lenticulina* forms belong to cosmopolites, which are characterized by phylogeny of this type and are widespread in the Boreal, Arctic, Notal, and Tropical zoochores.

Quite different situation is characteristic of phylogenetic development of the so-called "larger" foraminifers representing endemic Tethyan genera from families Lituolidae, Cyclamminidae, Pfenderinidae, Spirocyclinidae, and, partly, Ataxophragmiidae. These dominant forms that occupied Jurassic tropical seas gave their name to the peculiar cyclamminid–pfenderinid fauna of the Tethyan foraminifers. As compared with the first group, this fauna is characterized by quite different parameters: lower tolerance (ecological valence) owing to a higher specialization level, intricate morphology of dominants, higher evolution rate at the generic and species levels, lower species diversity of genera (mostly mono- or oligotaxonic), and limited adaptive area. Contrary to the "bunch-type" evolution, phylogeny of these forms can be termed as "linear," because species successively replacing each other form a continuous chain of forms genetically connected in every phylogenetic lineage.

Development of "intricate" lituolids and pfenderinids and evolution of their morphological features (Figs. 5–7) was studied in detail by Septofontaine (1988). Faunas of this type lived in shallow tropical

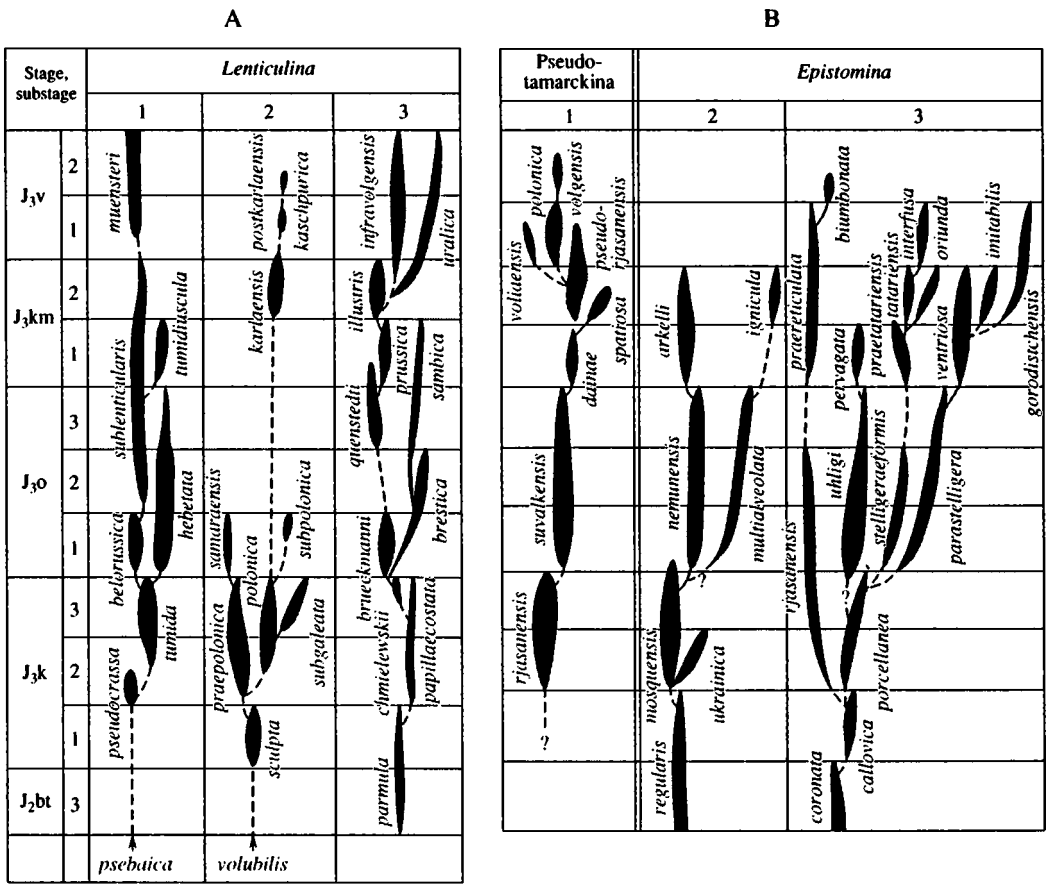

Fig. 2. Phylogenetic development of Late Jurassic foraminifers. (A) Genus *Lenticulina*: (1) *Lenticulina tumida* group, (2) *L. polonica* group, (3) *L. brueckmanni* group; (B) Genera *Pseudolamarckina* and *Epistomina:* (1) *Pseudolamarckina rjasanensis* group, (2) *Epistomina mosquensis* group, (3) *E. callovica* group (after Grigyalis, 1985). Morphogenesis is expressed in the increased thickness of a test (d/H), median height of the apertural surface, and total diameter of a test (*L. tumida* group), as well as in decreased elongation degree (D:d) and relative height of the apertural surface (*L. brueckmanni* group). The *Pseudolamarckina rjasanensis* group developed toward an increase in test convexity, thickness of sutures, and number of chambers. Development of the *Epistomina mosquensis* group is expressed in intricate surficial ornamentation, decreased convexity, and higher number of chambers in the Oxfordian forms, and, to the contrary, in simpler ornamentation, decreased number of chambers, and lesser general dimensions of the Kimmeridgian tests.

seas of the Jurassic time. They included the following Jurassic genera: *Amijiella, Alzonella, Alveosepta, Anchispirocyclina, Bramkampella, Charentia, Choffatella, Coskinolina, Dhrumella, Everticyclammina, Feurtillia, Flabellocyclolina, Haurania, Kilianina, Kurnubia, Lucasella, Mayncina, Meyendorffina, Orbitammina, Orbitopsella, Parurgonina, Paleopfenderina, Praekurnubia, Pseudocyclammina, Rectocyclammina, Spirocyclina, Sanderella, Steinekella, Satorina, Timidonella, Torinosuella,* and others. This list is far from being complete and includes endemic tropical genera representing forms with an intricate structure of exo- and endoskeletons and with the alveolar labyrinth-type walls and septa of agglutinated tests. The study of foraminifers from Jurassic deposits of the Eastern Mediterranean revealed that this type of fauna is characterized by several peculiar features untypical of cosmopolitan forms (both secretory and agglutinated). First of all, the species composition of genera is extremely impoverished, and only some of them include three to four species, whereas most are represented by one or two species (Figs. 5–7). Moreover, only few of these species coexisted. It should be remembered that the characteristic cosmopolitan genus *Lenticulina* includes up to 40 species, which existed simultaneously. The same is also characteristic of many other cosmopolitan genera. An important point is that different types of phylogeny ("bunch-type" and "linear") are clearly manifested at the *species* level, whereas the situation with higher taxa is different. Cosmopolitan genera, most of which appeared prior to the Jurassic, were represented in this period by parallel phylogenetic branches diverging from a single stem (family) of the preceding epochs (Triassic–Late Paleozoic). The endemic mono- and oligotaxonic genera that are characterized by the "linear" type of species evolution had

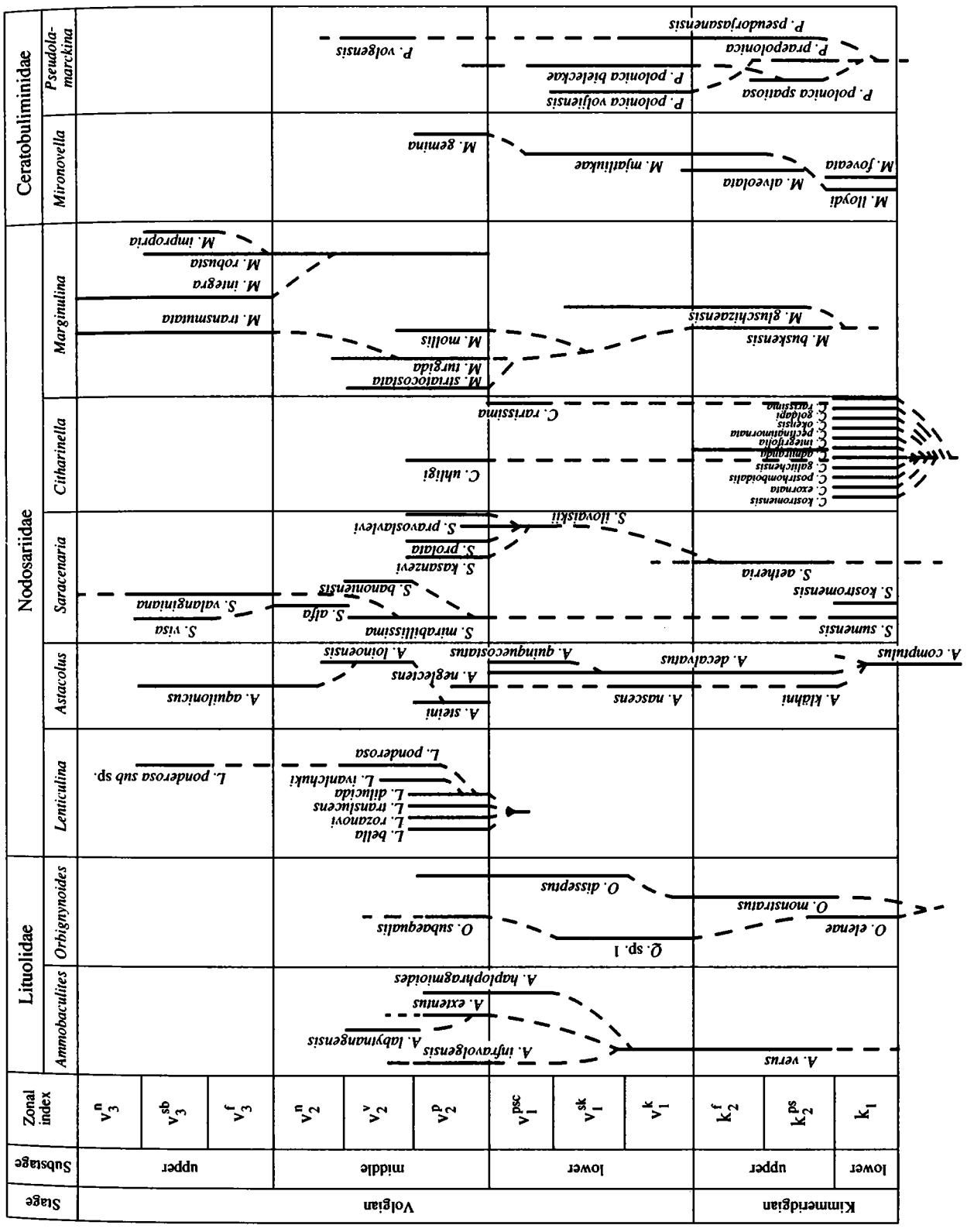

Fig. 3. Presumed phylogenetic development of some foraminiferal genera in the Kimmeridgian and Tithonian, the nodosariid–epistominid type of fauna (after Kuznetsova, 1979).

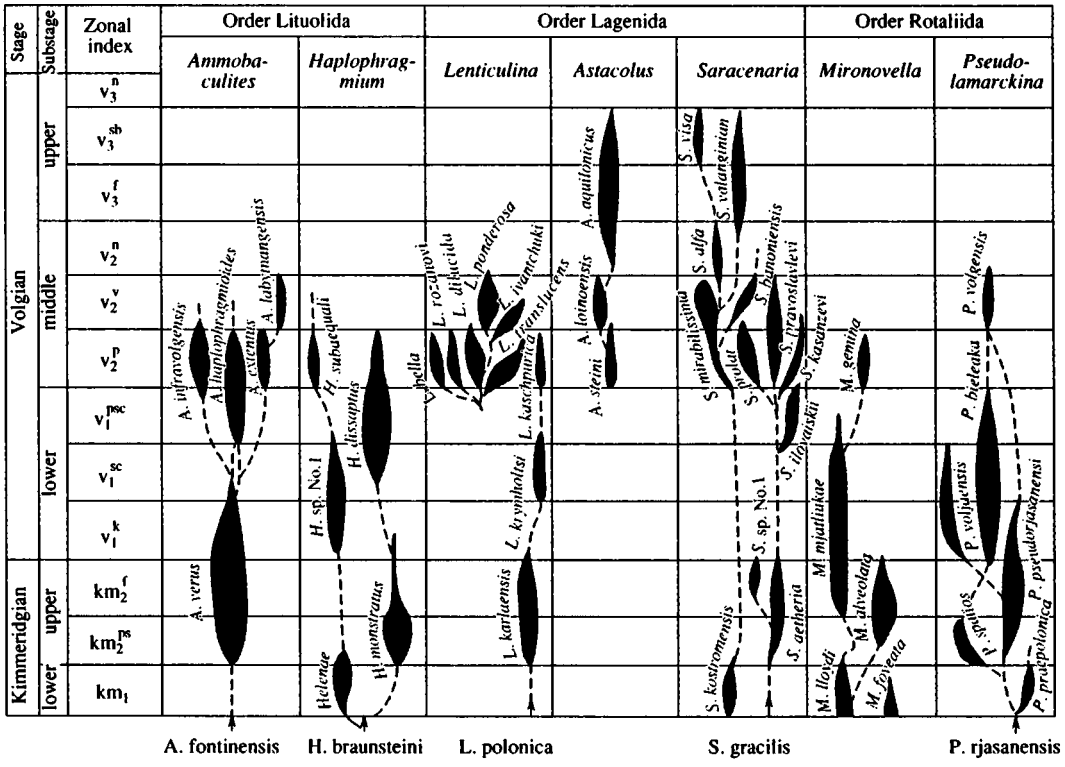

Fig. 4. Presumed phylogenetic development of some genera of secretory and agglutinated foraminifers in the terminal Jurassic (after Dain and Kuznetsova, 1976).

the diversification peak precisely in the Jurassic, when a peculiar "bunch" of genera appeared simultaneously in some families. Thus, the two groups under consideration show the opposite trends of higher taxa and species evolution.

For instance, 9 new genera appeared simultaneously in the Pliensbachian–Sinemurian taking origin from the earlier genus *Lituolipora* (order Lituolida). After low-rate radiation at the Early–Middle Jurassic boundary time, additional 8 and 10 genera appeared in the Bajocian–Bathonian time within the orders Ataxophragmiida and Orbitolinida, respectively. In other words, about 20 new genera of "larger" foraminifers appeared almost instantly in terms of geological time (Figs. 8, 9). In more detail, these topics are discussed by Basov and Kuznetsova (2000).

In addition, the structure of communities of endemic Tethyan genera also appears to be different than that of cosmopolitan ones, if we compare such parameters as the species diversity index (ratio between numbers of species and genera, or S/G) and abundance of every species in a separate layer (sample) that reflects, to some extent, the density of species populations. While the S/G parameter ranges from 1–1.1 to 2–2.3, an individual abundance of not numerous endemic species can sometimes amount to 100 specimens and more. This is particularly characteristic of genera *Kurnubia, Choffatella, Haurania, Pseudocyclammina*, and, less commonly, of *Anchispirocyclina* and *Alveosepta* but is absolutely untypical of such genera as *Flabellocyclolina, Meyendorffina, Praekurnubia*, and *Timidonella*. In addition to their limited distribution area (Tethyan endemics), the second remarkable feature of the generic group under discussion is a short-term existence of species and generic taxa. Almost all of them appeared in the Jurassic since the Pliensbachian, widely developed in the Bajocian-Bathonian, and became mostly extinct by the end of the Jurassic. It should be emphasized that this group of endemic genera is the only one amid diverse Jurassic foraminifers. It appeared in the Jurassic Tethyan seas and continued to live in tropical basins up to extinction contrary to most genera, which first occupied a part of some zoochore and then gradually became globally distributed, i.e., cosmopolitan.

The above peculiarities of the considered groups (highly specialized endemics and tolerant cosmopolites) reveal interrelationship of such parameters as the evolution rate of taxa, limits of their adaptive areas, and duration of existence (life time). All cosmopolitan species that lived (and mostly appeared) in the Jurassic or earlier continue to exist up to the Holocene and are widespread in sediments of modern seas. These are *Reophax, Trochammina, Lenticulina, Nodosaria* (since

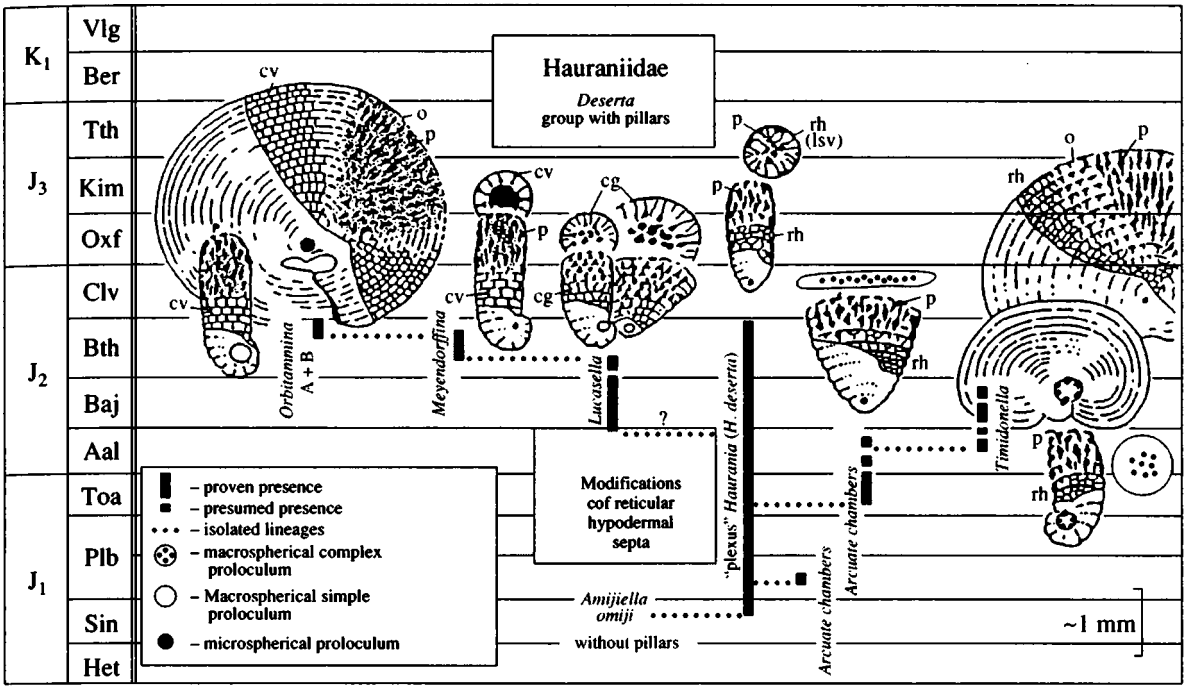

Fig. 5. Presumed phylogenetic development of the Hauraniidae group with pillars in the central part of a chamber. A system of thin subvertical septa (as in the genus *Lucasella*) can originate from the reticular hypodermal layer by compression of subhorizontal plates. Irregular subvertical septa can be later transformed into the vertical (regular) radial ones as in the *Meyendorffina–Orbitammina* group. Stolons are radial. Wall and inner margin of chambers: (rh) reticular hypodermal layer, (lsv) subvertical plates, (cg) thin subvertical septa, (cv) vertical radial septa. The central part of a chamber: (p) subcylindrical pillars, (o) multiple perforate aperture (after Septfontaine, 1988).

the Permian), *Marginulina, Marginulinopsis* (since the Triassic), *Vaginulina, Globulina* (since the initial Jurassic), *Cribrostomoides, Recurvoides* (since the second half of the Jurassic), and others. Genera with more restricted distribution areas such as *Citharinella* (Boreal part of Europe and North America) are characterized by shorter periods of life (Middle Jurassic, Bathonian–Late Cretaceous, Campanian). Endemic genera characteristic only of the Boreal Jurassic existed even during a shorter time. For instance, genus *Spirofrondicularia* existed since the Late Jurassic (Tithonian Age) to the Early Cretaceous (Aptian) and was distributed only in seas of the Russian platform and England. Genus *Mironovella* (also Boreal endemic) is known from the Late Jurassic (Kimmeridgian) up to the Early Cretaceous (Hauterivian). The distribution area of the last species is restricted to the Russian platform, Poland, England, and Germany. There are also ephemeral genera that existed only a single age, e.g., *Rectoepistominoides, Spirotrocholina*, and others. In other words, taking Jurassic foraminifers as an example, one can see the direct correlation between the lifetime of taxa and dimensions of their distribution areas. The analysis of distribution areas of supergeneric taxa and duration of their existence reveals another regularity: none of genera that existed during the Jurassic (some of them became extinct during this period) reduced its adaptive area. Moreover, most of them widened their distribution areas, sometimes to the global one. As was mentioned, the highly specialized Tethyan endemics represent an exception. In my opinion, explanation to this fact can be found in the so-called "law of an unspecialized" (Cope, 1896). According to this law, highly specialized dominant taxa represent dead ends of evolution and only "unspecialized" taxa give rise to new evolutionary lines (Krasilov, 1977). Let us remember that the considered endemic genera belong to the so-called "intricate" or "larger" lituolids and pfenderinids with an extremely high specialization degree that is expressed in the complex structure of the exo- and endoskeletons. This determined a low tolerance or ecological valence of these forms and their vulnerability under an environmental stress. Their selective tolerance to environments was so high that these organisms could adapt only small areas of the basin and only for a short period. This can be exemplified by genera *Kilianina* and *Meyendorffina* (the Bathonian of the southern France and Syrian basins only), *Flabellocyclolina* (Oxfordian of Israel, Santonian of France), *Timidonella* (Middle Jurassic of France, Italy, and Eastern Mediterranean), *Paracyclammina* (Late Jurassic of Indonesia), *Alzonella* (Bathonian of France and Syria), and *Bramkampella* (Tithonian–Berriasian of Syria, Saudi Arabia, and Crimea).

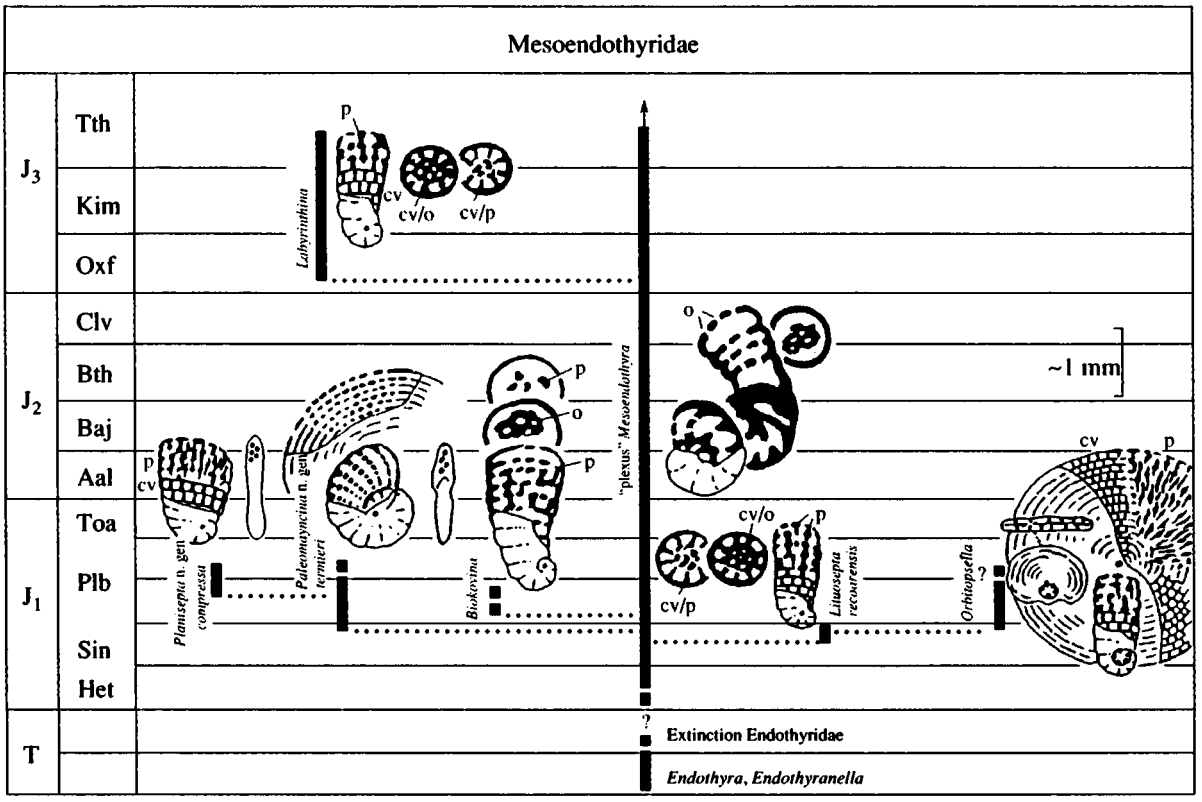

Fig. 6. Presumed phylogenetic development of some genera of order Lituolida. An irregular spire (genus *Mesoendothyra*) is transformed into the low one in more advanced taxa of this group. The presence of keriotheca is characteristic of all representatives of the group. Also present are vertical radial septa and pillars. Stolons are radial. The inner structure of chambers: (cv) vertical radial septa, (p) subcylindrical pillars, (o) multiple perforate aperture (after Septfontaine, 1988).

The cited examples of highly tolerant cosmopolitan genera that existed since the Jurassic up to present-day and specialized low-tolerance endemic genera that existed only two–three geological ages are extreme end members in the adaptive chain of these forms. Naturally, the interval between these extreme taxa comprises forms with more or less prolonged lifetime and relatively wider distribution area. However, all of them confirm the above-noted correlation between the lifetime and distribution area.

Earlier, it was mentioned that Jurassic foraminiferal communities show a distinct tendency of the diversity increase (at all taxonomic levels) and ecological diversification. Krasilov (1977) emphasizes that diversification develops owing to adaptation to different habitats under the influence of competition within groups and is accompanied by a wide distribution and significant abundance. Usually, the appearance and diversification are separated by a prolonged time period. None of these most important parameters (time for adaptation to and occupation of the habitat area, wide distribution area, and high abundance) was characteristic of the considered group of endemic Tethyan genera. Therefore, the group represents a unique example of evolution in the foraminiferal communities that were characterized by specific features and unusual type of development, although similar examples are known from other periods of fauna evolution. These are Paleozoic fusulinids (order Fusulinida Wadekind, 1937), similarly large (up to 15 mm in diameter) and highly specialized benthic forms with the intricate internal structure of a test having external wall and endoskeleton.

Another example is the order Orbitolinida Bashkirov et Antonischin, 1974. Orbitoids whose representatives also have large (up to 12 mm in diameter) intricate test appeared at the very end of the Mesozoic (Campanian) and existed up to the terminal Miocene. The order includes about 30 genera. They were also dwellers of shallow warm seas and, similar to Paleozoic fusulinids, were characterized by the inactive mode of life. Lifetime periods of fusulinids, Jurassic intricate lituolids and pfenderinids, and orbitoids were about 110, 60, and 55 m.y., respectively, separated by significant intervals. All these groups had restricted adaptive areas that remained unchanged during their entire existence period, complex morphotypes of dominants, high level of specialization, low tolerance degree, and a relatively short (as compared with cosmopolites) lifetime.

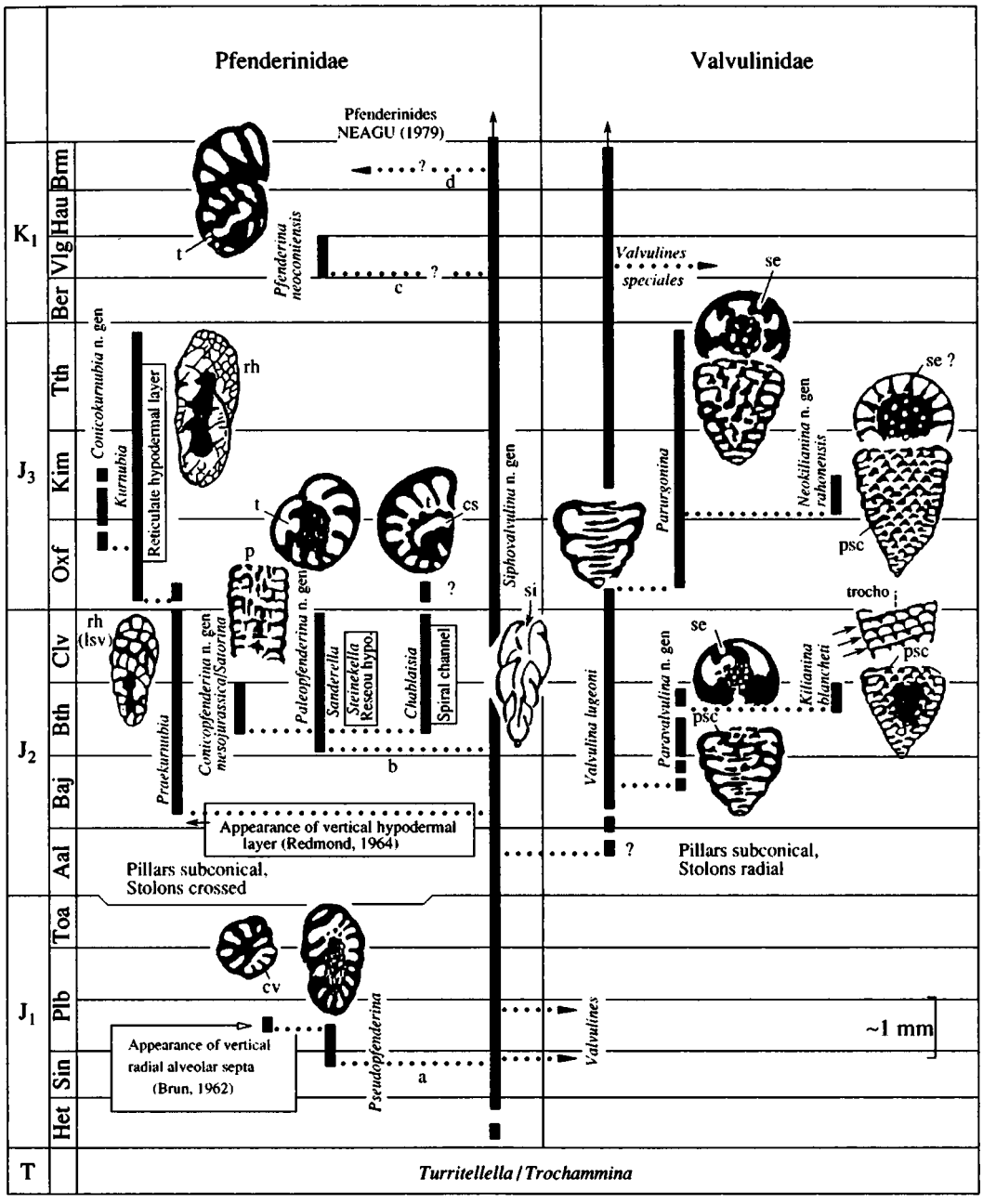

Fig. 7. Presumed phylogenetic development of trochospiral Lituolidae, Pfenderinidae, and Valvulinidae. Pfenderinids are characterized by presence of subcylindrical pillars in the axial zone of a test (stolons are radial), which appear as thick columellae after deposition of secretory calcite between pillars. Columellae can have secondary channels and furrows. The test wall and marginal part of a chamber can have different microstructures: keriotheca, reticular hypodermal layer, or vertical radial septa. The wall and inner margin of a chamber: (rh) radial hypodermal layer, (sv) subvertical plates, (cv) vertical radial septa. Axial part of a test: (p) subcylindrical pillars, (t) tunnel, (cs) spiral channel. The basal part of a test: (se) septa. The axial zone of a test: (psc) subconical pillars, (si) siphon (after Septfontaine, 1988).

This is the phylogenetic aspect in development of Jurassic foraminifers that is evolutionary in fact (Fursenko, 1950).

Another historical–faunal aspect of a complex evolutionary process is that considering development of all communities with time and in space. Taxonomic composition of faunas and changes in their diversity and geographic distribution are the main objects of study by such an approach.

Several distinct tendencies are evident from the analysis of composition of foraminiferal communities at all taxonomic levels, from species to order: (1) distri-

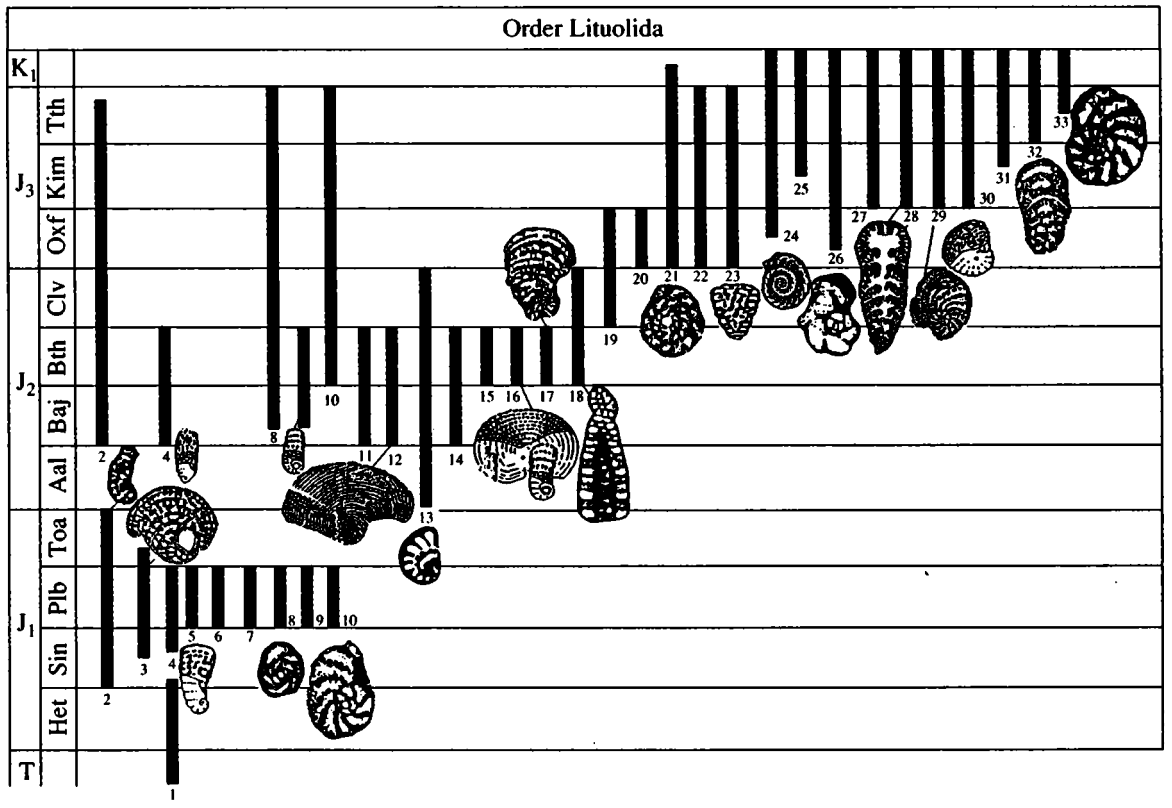

Fig. 8. Stratigraphic distribution of endemic genera of "intricate" lituolids in the Tethyan zoochore: (1) *Lituopora*; (2) *Labyrinthina*; (3) *Orbitopsella*; (4) *Haurania*; (5) *Brokovina*; (6) *Bosniella*; (7) *Cyclorbitopsella*; (8) *Pseudocyclammina*; (9) *Amijiella*; (10) *Streptocyclammina*; (11) *Limognella*; (12) *Timidonella*; (13) *Chablaisia*; (14) *Flabellaminepsis*; (15) *Orbitammina*; (16) *Arzonella*; (17) *Dhrumella*; (18) *Paracoskinolina*; (19) *Praekaraisella*; (20) *Karaisella*; (21) *Alveosepta*; (22) *Paracyclammina*; (23) *Parurgonina*; (24) *Choffabella*; (25) *Melathroherion*; (26) *Evertocyclammina*; (27) *Pseudospirocyclina*; (28) *Rectocyclammina*; (29) *Torinosuella*; (30) *Anchispirocyclina*; (31) *Audienusina*; (32) *Bramkampella*; (33) *Feurtillia*. Images in Figs. 8 and 9 are after Redmond (1964, 1965); Fourcade and Neumann (1966); Hottinger (1967); Pellisie *et al.*, (1984); Septfontaine, (1988); Kuznetsova *et al.*, (1996).

bution areas of most genera, which first occupied only a small part of the paleozoochore, widened to reach a subglobal dimension for many higher taxa; (2) most genera increased their species diversity; and (3) density of species populations progressively increased. It should be noted, however, that the last tendency is established only for some species and in some zoochores. The study revealed that the crisis tendencies and activated radiation of foraminiferal communities were in antiphase during some moments of their Jurassic history in different climatic zones. In my opinion, this is a consequence of the environmental influence on benthic organisms that was favorable or, to the contrary, unfavorable for them. This can be exemplified by development of foraminifers during the Bathonian when their communities in Arctic basins became substantially impoverished due to extinction of many species and genera, whereas those in the Tethyan tropical seas showed, in contrast, a sharp diversity increase and appearance of new genera and even families. The influence of facies and Jurassic landscape settings is well seen in Tethyan seas, where the carbonate platform destruction resulted in differentiation of the underwater topography, sharp lateral changes in composition and structures of bottom sediments, and in stratification of bathymetric zones. The response of communities to depth changes and, correspondingly, to the temperature of bottom waters and hydrodynamics was extremely rapid, as it is evident from frequent alternation of different foraminiferal assemblages through the section corresponding to a single age (stage). Precisely this repeated alternation of different communities points to ecological causes of the changes, i.e., to migration of biocoenoses together with favorable facies settings, rather than to evolutionary factors. Repeated alternations can also be related to the replacement of the carbonate sedimentation (in pure transparent water) by the clayey (terrigenous–carbonate) one, when the increased fluxes of clayey material resulted in a higher water turbidity and in silting of bottom sediments. In the last case, the "larger" foraminifers that preferred pure carbonate facies migrated to the other bottom

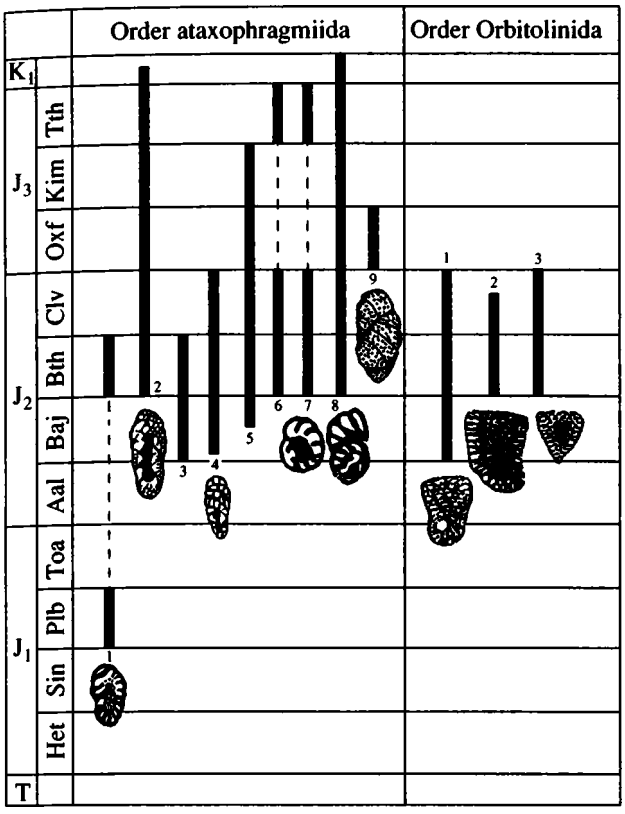

Fig. 9. Stratigraphic distribution of some endemic Tethyan genera of orders Ataxophragmiida (pfenderinids) and Orbitolinida. Order Ataxophragmiida: (1) *Pseudopfenderina*, (2) *Kurnubia*, (3) *Satorina*, (4) *Praekurnubia*, (5) *Pfenderina*, (6) *Sanderella*, (7) *Paleopfenderina*, (8) *Pfenderella*, (9) *Steinekella*. Order Orbitolinida: (1) *Gutnicella*, (2) *Meyendorffina*, (3) *Kilianina*.

areas and were replaced by species that populated the muddy substrate at the greater depth. Such distribution patterns of foraminiferal communities were observed in the Jurassic basins of Syria (Kuznetsova and Dobrova, 1995, 1997; Kuznetsova, 1998; Voznesenskii and Kuznetsova, 1999), Lesser Caucasus (Voznesenskii *et al.*, in press), and Crimea (Fedorova, 1999).

Thus, as is clearly evident from the study of relationships between taxonomic composition of benthic foraminifer communities and their habitats, the community types are dependent on ecological properties of the basin, which are responsible for the dispersion and migration of foraminifers but do not determine the trend and mode of their evolution only slightly influencing its rates, and do not stimulate generation of new higher taxa.

The discussed materials allow the following conclusions to be drawn:

(1) The study of evolutionary proper (phylogenetic) and historical–faunal aspects of evolution was used to discriminate faunal changes related to biological peculiarities of foraminifers and those caused by the influence of external, environmental factors. The first of them determine trend and mode of evolution, duration of the taxon lifetime, and type of phylogeny. Others are responsible for a high degree of ecological dependence of benthic foraminifers and directly influence their dispersion and migration and, to some extent, density of species populations.

(2) There are two main groups of Jurassic foraminifers that differ in biological parameters and type of phylogeny. They are discriminated using the following parameters: specialization degree, morphotypes of dominant taxa, tolerance level, distribution area (dimensions of the adaptation area), and evolution rates at the species and generic levels. One group includes the highly tolerant cosmopolitan taxa with the low specialization degree, whereas the other consists of endemic, intricate, highly specialized genera that populated tropical shallow seas. The first and second groups are characterized by the "bunch-type" and "linear" modes of evolution, respectively.

(3) The following main parameters show correlation between each other: specialization degree, lifetime duration, and distribution areas. The first parameter shows the negative correlation with two others. Consequently, every of these parameters can be used as representing a criterion for an approximate assessment of other parameters of taxa.

(4) All higher taxa of Jurassic foraminifers widened their distribution areas, except for the Tethyan endemics that remained within tropical basins since their origination till the extinction.

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Benthic Foraminifer Zonation in the Campanian–Maastrichtian of the European Paleobiogeographic Region

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Abstract—Present-day approaches to identification of stage and substage boundaries in the Campanian–Maastrichtian of the European paleobiogeographic region (EPR) are considered. A new zonation of the upper Santonian–Maastrichtian interval that is suggested in this work is based on traceable regularities in evolution of benthic foraminifer genera, which populated different EPR areas. The suggested zonal scheme includes 18 biostratigraphic subdivisions (13 zones and 5 subzones), all having a complex paleontological substantiation. These subdivisions are of different stratigraphic ranges. Those of shorter time spans characterize moments of regressions and incipient transgressions. Two paleobiogeographic provinces, the East and West European, are distinguished in the EPR for the considered interval of time. Despite the close similarity of foraminiferal assemblages, some of their species discriminate one province from another. The West European province was connected with the northwestern Atlantic Ocean better than with the Tethys. The East European province had connections not only with the Tethys, but also with boreal seas of West Siberia via the Middle Uralian, South Uralian, and Turgai straits.

Key words: European paleobiogeographic region, upper Santonian–Maastrichtian, benthic foraminifers, phylogeny, paleogeography.

INTRODUCTION

The epicontinental basin of the European paleobiogeographic region (EPR) was one of the largest in the Earth's history. It was about 7000 km wide and extended from the Atlantic Ocean in the west to the Kopet-Dag in the east (Fig. 1). This peculiar basin represented the northern epicontinental part of the Tethys (Peri-Tethys) and was less than 200 m deep. Chalk, marl, diverse limestones, and calcareous clay exemplify main products of background sedimentation in the basin. In addition to facies uniformity, these sediments are characterized throughout the region by similar assemblages of macro- and microfauna, which enable recognition of identical stratigraphic successions in various faunal groups.

STAGE AND SUBSTAGE BOUNDARIES

In the EPR, the Upper Cretaceous stage and substage boundaries are established in accord with distribution patterns of mollusks and echinoderms, which are well correlated with those of foraminifers (Koch, 1977; Naidin *et al.*, 1984a, 1984b; Schoenfeld, 1990; Schoenfeld and Burnett, 1991).

The Santonian–Campanian boundary corresponds to the disappearance level of *Marsupites testidinarius* (Hancock and Gale, 1996) that coincides with the first occurrence level of *Goniotheutis granulataquadrata* in southwestern Germany (Shulz *et al.*, 1984). In the East European platform, this boundary is placed at the base of the so-called "Pteriaceae Beds" and inside the *Bolivinoides strigillatus* Zone of benthic foraminifers (Koch, 1977; Naidin and Ivannikov, 1980; Naidin *et al.*, 1984a, 1984b).

The Campanian substages are defined in the EPR on the basis of zonal assemblages depicting phylogeny of belemnites, sea urchins, inocerams, ammonites, and foraminifers. The Campanian Age is longest one in the Late Cretaceous (10–11 m.y.). In the current schemes, it is subdivided in two substages only (Koch, 1977; Naidin and Kopaevich, 1977; Naidin *et al.*, 1984a, 1984b), whereas the shorter Coniacian Age (1 m.y. long) includes three substages (Kauffman *et al.*, 1996). Following Kopaevich *et al.* (1999), we suggest to distinguish three Campanian substages as well (Table 1). The lower Campanian should correspond to the evolutionary phase of belemnites *Goniotheutis* ex gr. *quadrata, Actinocamax laevigatus*, and *Belemnitella* ex gr. *praecursor* associated with first *Belemnitella mucronata* (e.g., *mucronata alpha*). The middle substage can be considered as spanning the range to the *Belemnitella mucronata* Zone that corresponds to the first occurrence level and further evolution of benthic foraminifers of the *Brotzenella monterelensis* Zone. The upper Campanian would begin from the first occurrence level of *Belemnitella* ex gr. *langei* and benthic

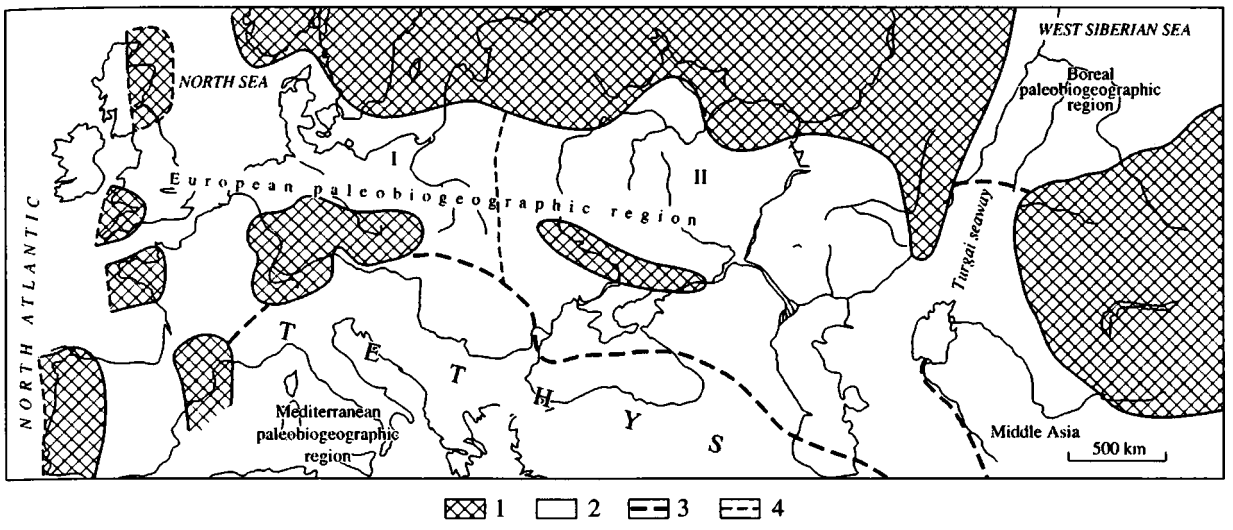


Fig. 1. European paleobiogeographic region (EPR), its provinces, and relations with other paleobiogeographic regions: (1) land; (2) sea; (3) boundary between regions; (4) boundary between West (I) and East European (II) provinces.

foraminifers *Globorotalites emdiensis* and *Bolivina kalinini*. As a result, the Campanian would be divided into the natural evolutionary phases of belemnites, ammonites, and foraminifers. Accordingly, its lower, middle, and upper substages can be exemplified by the *quadrata, mucronata*, and *langei* chalks, respectively.

The Campanian–Maastrichtian boundary is distinctly marked by the almost complete disappearance of *Belemnitella* ex gr. *langei* and by the simultaneous mass appearance of *Belemnella* forms, such as *B. licharewi* and *B. lanceolata*. This biotic event reflects an important change in the oceanic sphere of the Earth (Naidin, 1995). According to distribution of benthic foraminifers, the boundary in question is detected in the lower part of the *Angulogavelinella gracilis* distribution range (Akimets *et al.*, 1991).

The above idea to define the Campanian–Maastrichtian boundary at the first occurrence level of *Belemnella* forms was approved in Copenhagen at the International Symposium on the Cretaceous Stage Boundaries (Birkelund *et al.*, 1984).

Such an approach to definition of stage boundaries changed significantly in recent time. The International Stratigraphic Commission (ISC) established principle of fixing these boundaries in the particular reference section. This is the so-called principle of Global Boundary Stratotype Section and Point (GSSP). The GSSP is a stratigraphic boundary described in publications and recognized in the concrete section of definite successive beds. The GSSP is a standard for determination of a given boundary that separates global stratigraphic (chronostratigraphic) units (Cowie, 1986).

In the eastern EPR (Ukraine, Russia, Kazakhstan, and Turkmenistan), there are many complete sections exhibiting transition from the Campanian to Maastrichtian. One of these is the exposure of Campanian–Maastrichtian marl and chalk beds in the Aktulagai Plateau cliffs (western Kazakhstan, the site located 150 km northward of the Atyrau, formerly Gur'ev). This exposure is easily accessible for examination, rich in belemnites and other macrofossils, and yielding diverse assemblages of foraminifers and nannoplankton (Akimets *et al.*, 1983).

At the workshop of the Maastrichtian working group of the Cretaceous Subcommission of the ISC (Brussels, 1995), the main attention was paid to a section that was suggested as the GSSP of the Campanian–Maastrichtian boundary but never was discussed before. This was the Tercis Quarry section located at the left side of the Adour River southwestward of the Dax in the Pyrenees piedmont, department Landes of France (Odin, 1996). Naidin (1996) earnestly argued against this GSSP of the Campanian–Maastrichtian boundary using the following arguments: (1) different researchers variably identified the ammonite species *Pachydiscus neubergicus* whose appearance level defines the Campanian–Maastrichtian boundary in the Tercis section; (2) *Pachydiscus neubergicus* is a very rare form in the eastern EPR, where its distribution range is extremely reduced (uppermost lower–initial upper Maastrichtian); (3) ammonites, inocerams, and echinoids are extremely rare here, whereas belemnites do not occur at all; (4) the majority of ammonites pictured in plates originate not from the Tercis section, but from exposures along the Vistula River of Poland; (5) microfossils, such as nannoplankton, planktonic and benthic foraminifers, occur scarcely and are poorly preserved.

Arkhangel'skii (1912, 1934) was first to distinguish two Maastrichtian substages in the eastern EPR: the lower one corresponding to the *Belemnella* ex gr. *lan-*

Table 1. Upper Cretaceous zones of various macrofauna groups in the eastern EPR (after Naidin *et al.*, 1984a, with additions)

Stage, substage		Zone		Index
Maastrichtian	upper	*Neobelemnella kazimiroviensis*		m_2
	middle	*Acanthoscaphites tridens*	*Belemnella sumensis*	m_1^3
			Belemnella lanceolata	m_1^2
			Belemnella licharewi	m_1^1
Campanian	upper	*Belemnitella langei*	*Belemnitella langei najdini*	cp_3^3
			Belemnitella langei langei	cp_3^2
			Belemnitella langei minor	cp_3^1
	lower	*Belemnitella mucronata mucronata-Hoplitoplacenticeras coesfeldiense*		cp_2
	middle	*Gonioteuthis quadrata gracilis-Belemnellocamax mammilatus*		cp_1^3
		Gonioteuthis quadrata quadrata-Belemnitella mucronata alpha		cp_1^2
		Actinocamax laevigatus-Belemnitella praecursor mucronatiformis. Pteriaceae Beds of East European platform		cp_1^1
Santonian	upper	*Gonioteuthis granulata – Inoceramus patootensis* In the Mangyshlak and Crimea: *Uintacrinus* (below) and *Marsupites*		st_2
	middle	*Sphaenoceramus cardissoides* *Cladoceramus undulatoplicatus* at the base		st_1
Coniacian	upper	*Volviceramus involutus*		cn_2
	middle	*Inoceramus schloenbachi*		cn_1
Turonian	upper	*Inoceramus costellatus – Mytiloides striatoconcentricus*		t_3
	lower	*Inoceramus lamarcki* *Inoceramus apicalis* at the base		t_2
	middle	*Mytiloides hercynicus* *Mytiloides labiatus* *Praeactinocamax plenus triangulus*		t_1
Cenomanian	upper	*Inoceramus pictus bohemicus-Praeactinocamax plenus planus*		cm_3^2
		Eucalycoceras pentagonum		cm_3^1
	lower	*Inoceramus crippsi*	*Acanthoceras jukesbrownei*	cm_2^3
			Turrilites acutus	cm_2^2
			Turrilites costatus	cm_2^1
	middle		*Mantelliceras mantelli and Schloenbachia varians*	cm_1

ceolata Beds and the upper substage correlated with the *"Belemnitella" americana* Beds. We suggest to place the boundary between substages at the first occurrence level of *Neobelemnella kazimiroviensis* (Skolozdrówna) (= *B. americana*) associated with species transitional between *Belemnella* and *Neobelemnella* forms. This boundary simultaneously corresponds to the appearance level of benthic foraminifers of the *Brotzenella praeacuta* assemblage (Akimets *et al.*, 1983; Naidin *et al.*, 1984a, 1984b; Kopaevich *et al.*, 1987). One of the typical sections exemplifying transition from the lower to upper Maastrichtian is situated at

the Boktygaryn Cupola of the Caspian syneclise (Kopaevich *et al.*, 1987). In the West European schemes, the upper Maastrichtian includes the lower *Belemnitella junior* and upper *Belemnella kazimirovi-ensis* zones. In the eastern EPR (eastward of Donbass), species *B. junior* Nowak is unknown. Apparently, we deal here with the total range zone of *N. kazimirovi-ensis*, whereas only the teilzone of this species is detectable in the western EPR (Naidin, 1996; Kopaevich *et al.*, 1987).

BENTHIC FORAMINIFER ZONATION IN UPPER SANTONIAN AND MAASTRICHTIAN OF THE EPR

Chalk and marl facies of the EPR yield abundant and diverse benthic foraminifers, whereas coexisting planktonic forms are less diverse and concentrated at the particular levels corresponding in the eastern EPR to the periods of incipient transgressions and high sea-level stand. In general, the Upper Cretaceous deposits bear foraminifers with calcareous walls, which represent *Lenticulina, Robulus*, and *Neoflabellina* genera of nodosariids, and *Stensioeina, Valvulineria, Globorotalites, Gyroidinoides, Osangularia, Gavelinella, Brotzenella, Cibicidoides, Anomalinoides, Bulimina, Buliminella, Bolivina*, and *Bolivinoides* genera of rotaliids. These associate with some agglutinated genera having arenaceous walls, e.g., with *Spiroplectammina* forms of textulariids and with *Arenobulimina, Gaudryina, Ataxophragmium, Heterostomella, Orbignyna*, and *Voloshinovella* genera of ataxophargmiids.

Zonation of benthic foraminifers is based on representatives of those genera, which are well-studied, widespread, and exemplifying characteristic phylogenetic lineages. These are *Heterostomella, Neoflabellina, Globorotalites, Stensioeina, Osangularia, Gavelinella, Brotzenella, Cibicidoides, Bolivina*, and *Bolivinoides.*

The lower Campanian of the eastern EPR (Mangyshlak–Peri-Caspian region and East European platform) is characterized by the following zonation of benthic foraminifers: *Bolivinoides strigillatus* Zone XII (uppermost upper Santonian–basal lower Campanian); *Gavelinella clementiana* Zone XIV, *Bolivinoides decoratus* Zone XV; *Cibicidoides temirensis* Zone XVI; *C. aktulagayensis* Zone XVII (Naidin *et al.*, 1984a, 1984b; Akimets *et al.*, 1991; Roman figures indicate the succession of zones in Table 2 and Fig. 2).

In the Upper Cretaceous zonation accepted in Poland (Gawor-Biedowa *et al.*, 1984), the Santonian–Campanian boundary corresponds to the level separating the *Bolivinoides strigillatus* Zone that includes *Gavelinella clementiana, Stensioeina pommerana*, and *Globotruncana arca* in its lower part from the *Bolivinoides decoratus* Zone containing *Cibicidoides involutus* (= *C. aktulagayensis*).

In northwestern Germany, the Santonian–Campanian boundary is placed, like in the eastern EPR, inside the *Bolivinoides strigillatus* Zone. The higher succession of *Gavelinella clementiana, Neoflabellina wedeekindi*, and *Bolivinoides decoratus/granulatus* zones is close to that of the East European zonation (Koch, 1977; Schoenfeld, 1990).

In Czech Moravia belonging to the northern Tethyan region, dominant are planktonic foraminifers. Characteristic benthic form *Bolivinoides decoratus* appears here in the lower Campanian (Hanzliková, 1972).

The middle Campanian of the Mangyshlak–Peri-Caspian region corresponds to the *Brotzenella monterelensis* Zone XVIII. The first occurrence level of this taxon marks the upper boundary of the lower Campanian in the East European platform, Poland, Mons basin, and Aquitaine (Plattel, 1977; Gawor-Biedowa *et al.*, 1984; Robaszynski and Christensen, 1989; Akimets *et al.*, 1991; Gawor-Biedowa, 1992).

The upper Campanian of Mangyshlak–Peri-Caspian region includes a succession of the *Cibicidoides voltzianus* (XIX), *Bolivinoides miliaris* (XX), and *Brotzenella taylorensis* (XXI) foraminiferal zones.

In the upper Campanian of northwestern Germany, there are distinguished the lower *Cibicidoides voltzianus* and upper *Bolivinoides miliaris/Bolivina incrassata* Zones (Koch, 1977; Schoenfeld, 1990), and their succession is close to the previous one. A similar distribution of late Campanian foraminifers is recorded in the Mons basin of Belgium, where their assemblage includes characteristic species *Brotzenella monterelensis, Cibicidoides voltzianus, Globorotalites hiltermanni* (= *G. emdyensis*), *Gavelinella lorneiana* (= *G. clementiana clementiana*). *Bolivinoides australis* (= *B. decoratus giganteus*), and *Bolivina incrassata* (Robaszynski and Christensen, 1989).

Lower Maastrichtian. In the eastern EPR, the Campanian–Maastrichtian boundary is identified at the base of the *Angulogavelinella gracilis* Zone XXII that also yields *Neoflabellina reticulata, Osangularia navoroanna, Bolivinoides peterssoni*, and *Bolivina decurrens.* Two higher zones of *Brotzenella complanata* (XXIII) and *Bolivinoides draco draco* (XXIV) include as well *Coleites crispus* and *Bolivina incrassata crassa* (= *B. incrassata gigantea*).

The *Angulogavelinella gracilis* level corresponds to the Maastrichtian base in Sweden (Brotzen, 1945). In northwestern Germany, the Campanian–Maastrichtian boundary corresponds to the base of the *Bolivinoides decurrens* Zone. Above the latter, there is the *Neoflabellina reticulata* Zone. The *Bolivinoides draco draco* Zone also yielding *Coleites reticulosus* spans an upper part of the lower Maastrichtian

The upper Maastrichtian of the eastern EPR is subdivided into the *Brotzenella praeacuta* (XXV) and *Hanzawaia ekblomi/Pseudotextularia elegans* (XXVI) zones. The first occurrence level of *P. elegans* charac-

Table 2. Benthic foraminiferid zonation in the Upper Cretaceous of the eastern EPR

Index	Zone	Zone no.
m_2	*Hanzawaia ekblomi, Anomalinoides pinguis, Gavelinella gr. danica, Pseudotextularia varians, P. elegans*	XXVI
m_1^3–m_2	*Brotzenella praeacuta, Cibicides kurganicus, Gavelinella pertusa, Tappanina selmensis*	XXV
m_1^3	*Bolivinoides draco draco, Coleites crispus, Gavelinella midwayensis, Stensioeina caucasica*	XXIV
m_1^2	*Brotzenella complanata, Spiroplectammina suturalis, Gavelinella welleri, Anomalinoides subcarinatus, Bolivina incrassata incrassata, B. incrassata crassa*	XXIII
cp_3^3–m_1^1	*Angulogavelinella gracilis stellaria, Neoflabellina reticulata, Osangularia navarroana, Gyroidina globosa, Cibicidoides bembix, Bolivina deccurens, Bolivinoides delicatulus, B. peterssoni, Reussella minuta*	XXII
cp_3^3	*Brotzenella taylorensis, Neoflabellina praereticulata, Bolivina incrassata incrassata, Pseudouvigerina cristata, Bolivinoides giganteus,*	XXI
cp_3^2	*Bolivinoides draco miliaris, Eponides frankei, E. conspectus, Gavelinella cayexi mangyshlakensis, Bolivina kalinini, Gemellides orcinus, Rugoglobigerina rugosa*	XX
cp_3^1	*Cibicidoides voltzianus, Heterostomella foveolata, Plectina ruthenica, Globoratalites emdyensis, Gavelinella clementiana laevigata, Globotruncana morozovae*	XIX
cp_2	*Brotzenella monterelensis, B. menneri, Gavelinella clementiana usakensis, Arenobulimina convexocamerata, Heterostomella praefoveolata, Orbignyna sacheri, O. ovata, Voloshinovella tertia, V. laffitei*	XVIII
cp_1^3a	*Cibicidoides aktulagayensis, Plectina convergens*	XVII
cp_1^3b	*Cibicidoides temirensis, C. montanus, Eponides biconvexus, Bolivinoides laevigatus laevigatus, Bolivinitella galeata*	XVI
cp_1^2	*Bolivinoides decoratus decoratus, B. granulatus, Osangularia cordieriana, Globigerinelloides volutus*	XV
cp_1^1	*Gavelinella clementiana clementiana, G. dainae, Neoflabellina rugosa, Stensioeina pommerana, Reussella pseudospinulosa, Bolivinoides laevigatus finitima, Globotruncana arca*	XIV
st_2–cp_1^1	*Bolivinoides strigillatus, Ataxophragmium orbignynaeformis, Gavelinella stelligera, Globotruncana arcaformis*	XIII
st_2	*Osangularia whitei polycamerata, O. crassa, O. whitei whitei, Gavelinella gr. stelligera, Cibicides excavatus*	XII
st_1	*Stensioeina granulata perfecta, S. granulata incondita, S. exsculpta gracilis*	XI
cn_2–st_1	*Stensioeina exsculpta exsculpta, Gavelinella vombensis, G. umbilicatula, Cibicidoides eriksdalensis*	X
cn_2	*Stensioeina granulata granulata, Spiroplectammina embaensis, Valvulineria laevis, Gyroidina turgida, Globorotalites michelinianus, Osangularia whitei whitei, Gavelinella vombensis (=G. infrasantonica), G. thalmanni, G. costulata, Bolivinita eleyi*	IX
cn_1	*Reusella kelleri, Gavelinella praeinfrasantonica, Gavelinella kelleri, G. costulata, Stensioeina granulata kelleri, Marginotruncana coronata*	VIII
t_3	*Ataxophragmium nautiloides, Gavelinella gr. costulata, Cibicidoides praeeriksdalensis, Marginotruncana renzi*	VII
t_2	*Gavelinella moniliformis, G. ammonoides, Spiroplectammina praelonga, Gaudryina variabilis, Globorotalites multiseptus, Reussella carinata, Marginotruncana lapparenti, M. marginata, Hedbergella agalarovae*	VI
t_1^2	*Globorotalites hangensis, Spiroplectammina cuneata, Gaudryina subserrata, Gyroidina nitida, Valvulineria lenticula, Gavelinella vesca, Cibicidoides apprima*	V
t_1^1	*Hedbergella holzli, H. portsdownensis, Whiteinella brittonensis, W. archeocretacea, W. baltica, Globigerinelloides bentonensis*	IV
cm_{2-3}	*Lingulogavelinella globasa, Brotzenella berthelini, Gavelinella vesca*	III
cm_1	*Gavelinella cenomanica, G. baltica, Lingulogavelinella orbiculata, Cibicides polyrraphes polyrraphes, Neobulimina numerosa, Hedbergella caspia, Thalmanninella appenninica*	I–II

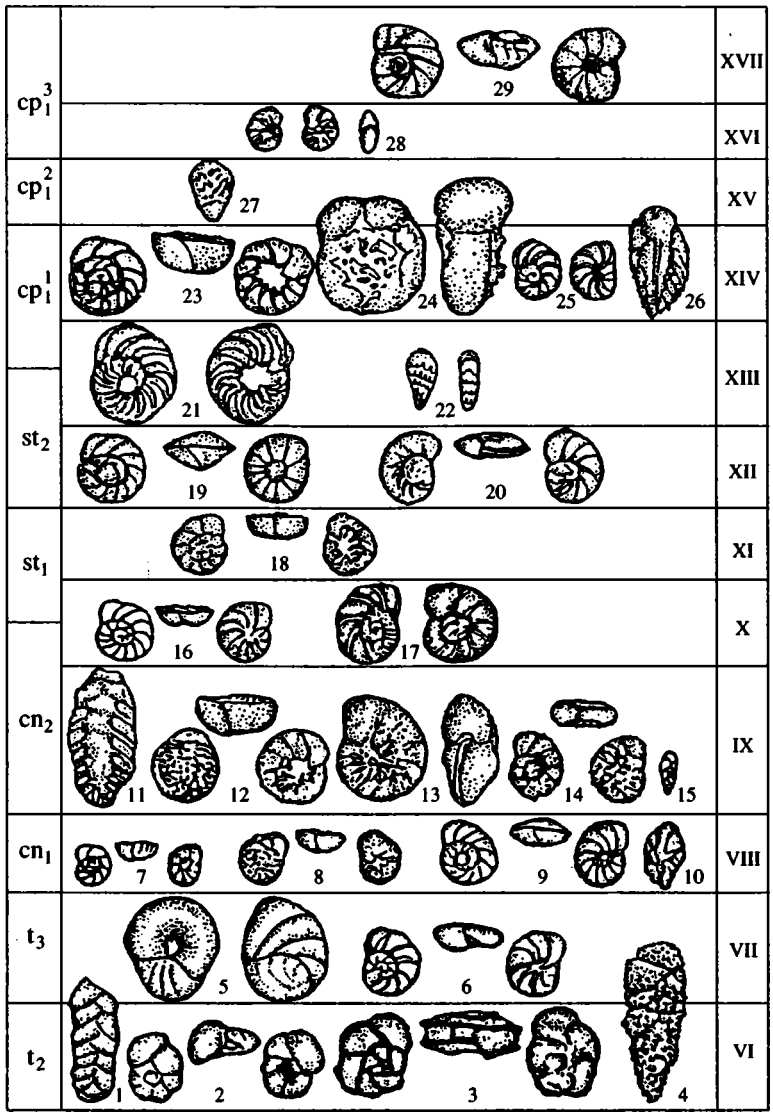


Fig. 2. Characteristic benthic foraminifers of Upper Cretaceous zonal assemblages of the eastern EPR: (1) *Spiroplectammina praelonga*; (2) *Gavelinella moniliformis*; (3) *Marginotruncana lapparenti*; (4) *Gaudryina variabilis*; (5) *Ataxophragmium nautiloides*; (6) *Gavelinella* gr. *costulata*; (7) *Stensioeina* sp.; (8) *S.* gr. *granulata*; (9) *Gavelinella praeinfrasantonica*; (10) *Reussella kelleri*; (11) *Spiroplectammina embaensis*; (12) *Stensioeina granulata granulata*; (13) *Gavelinella infrasantonica*; (14) *G. thalmanni*; (15) *Bolivinita eleyi*; (16) *Stensioeina exsculpta exsculpta*; (17) *Gavelinella umbilicatula;* (18) *Stensioeina granulata perfecta*; (19) *Osangularia whitei crassa*; (20) *Gavelinella* gr. *stelligera*; (21) *G. stelligera*; (22) *Bolivinoides strigillatus*; (23) *Stensioeina pommerana*; (24) *Gavelinella clementiana clementiana*; (25) *G. dainae*; (26) *Reussella pseudospinulosa*; (27) *Bolivinoides decoratus decoratus*; (28) *Cibicidoides temirensis*; (29) *Cibicidoides aktulagayensis*; (30) *Brotzenella monterelensis*; (31) *Globorotalites emdyensis*; (32) *Cibicidoides voltzianus*; (33) *Gemellides orcinus*; (34) *Bolivina kalinini*; (35) *Bolivinoides draco miliaris*; (36) *Brotzenella taylorensis*; (37) *Bolivina incrassata incrassata*; (38) *Angulogavelinella gracilis*; (39) *Bolivinoides delicatulus*; (40) *Brotzenella complanata*; (41) *Stensioeina* gr. *caucasica*; (42) *Gavelinella welleri*; (43) *Anomalinoides subcarinatus*; (44) *Coleites crispus*; (45) *Gavelinella midwayensis*; (46) *Bolivina incrassata crassa*; (47) *Bolivinoides draco draco*; (48) *Brotzenella praeacuta*; (49) *Cibicides kurganicus*; (50) *Hanzawaia ekblomi*; (51) *Anomalinoides pinguis*; and (52) *Pseudotextularia varians.*

terizes the terminal part of the upper Maastrichtian in Sweden and northwestern Germany.

Thus, there are two regions with detailed zonations of benthic foraminifers. These are the Mangyshlak–Peri-Caspian region in the east and the basin of northwestern Germany in the west of the EPR. Foraminiferal zonal scales of both regions are reliably correlated with zonations based on different groups of macrofauna (Koch, 1977; Naidin *et al.*, 1984a, 1984b; Schoenfeld, 1990; Schoenfeld and Burnett, 1991).

The detailed zonations of both the western and eastern regions were considered in a series of publications

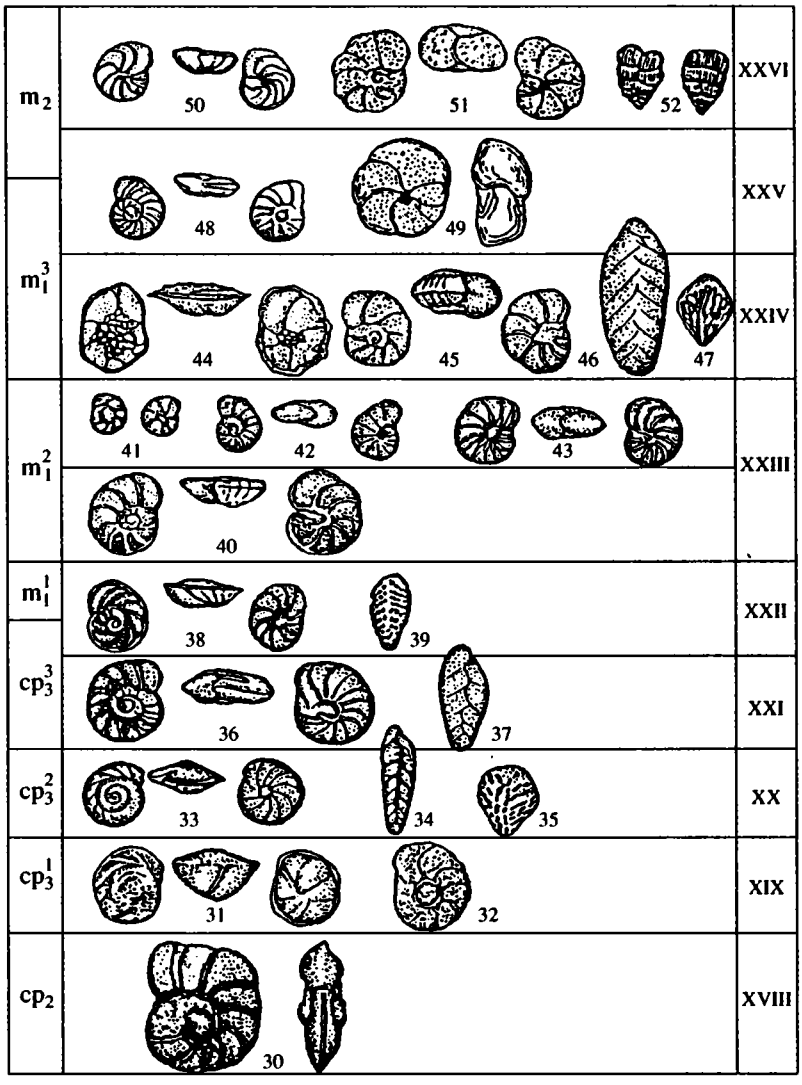


Fig. 2. (Contd.)

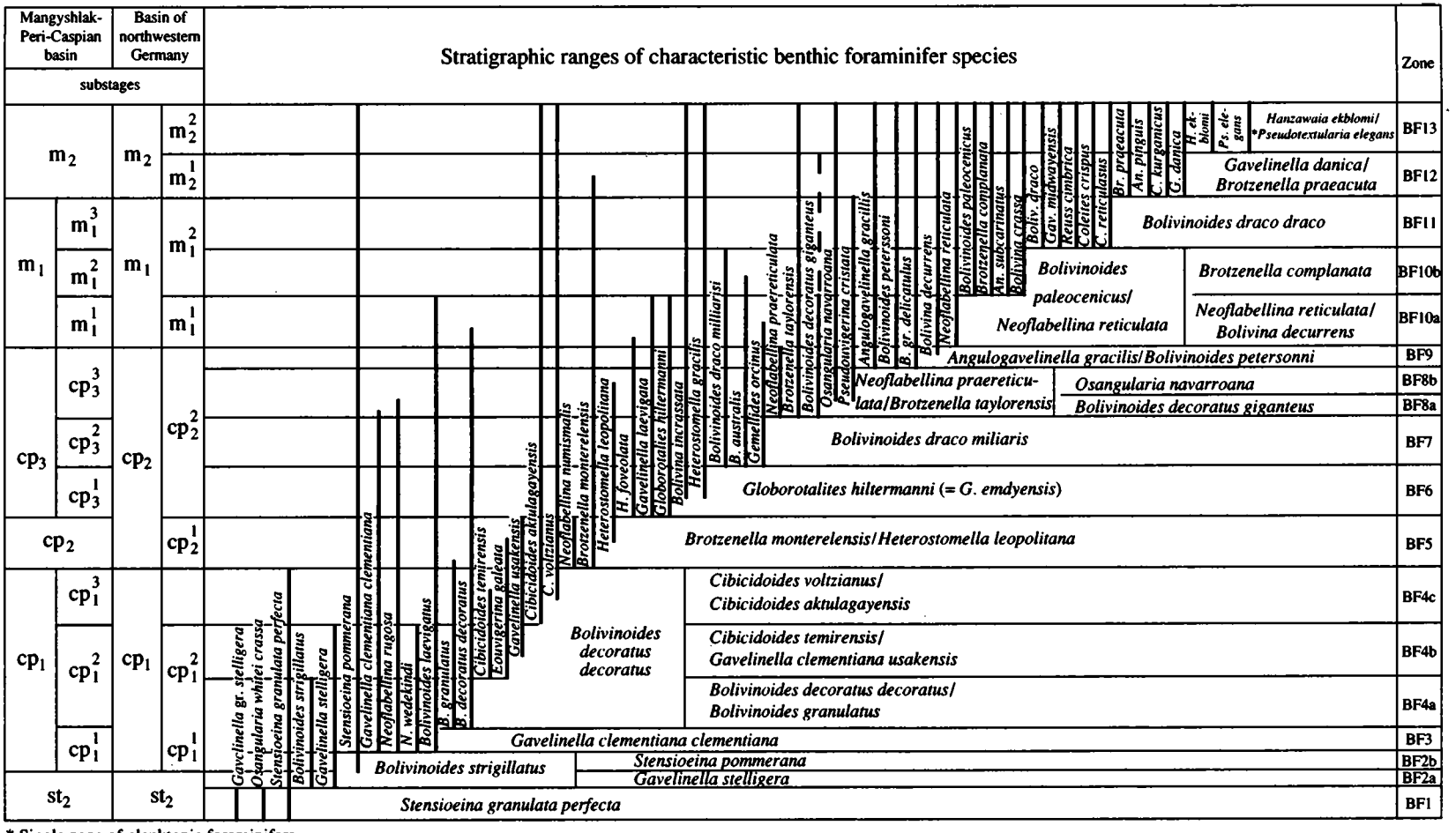
(Koch, 1977; Naidin *et al.*, 1984a, 1984b; Schoenfeld, 1990; Akimets *et al.*, 1991). The resulting integral scheme (Fig. 3) was first outlined by Beniamovskii and Kopaevich (1966).

This scheme includes 13 zones each having complex substantiation. All zones are named after their index species. They are designated by abbreviation BF meaning benthic foraminiferid zones (BF1, BF2, BF3, etc.). Zones BF2, BF8, and BF9 are divided into two subzones each, and three subzones are distinguished in Zone BF4. In total, there are 18 biostratigraphic units (zones and subzones) in the scheme. This highly detailed zonation elucidated positioning of the Santonian–Campanian and Campanian–Maastrichtian boundaries, which have been formerly placed inside zones and are now correlated with levels discriminating subzones BF2a and BF2b, and zones BF9 and BF10. Table 3 illustrates correlative levels of the suggested and other zonations available for the eastern and western EPR regions. We suggest to characterize most of biostratigraphic units by two index species: one characteristic of the eastern and other of the western EPR regions.

ZONES AND THEIR PALEONTOLOGICAL SUBSTANTIATION

Stensioeina granulata perfecta Zone BF1

W. Koch (1977) (= *S. granulata perfecta* Beds after Naidin *et al.*, 1984a, 1984b).



* Single zone of planktonic foraminifers.

Fig. 3. Details of benthic foraminiferid zonation in the Santonian–Maastrichtian of the eastern EPR.

Table 3. Benthic foraminiferid zonation in the Campanian–Maastrichtian in the EPR as compared to regional zonal scales

Mangyshlak–Peri-Caspian basin		Basin of northwestern Germany		Benthic foraminiferid zonation in the EPR			Regional zonal scales: Eastern EPR		Regional zonal scales: Western EPR	
Substages and their parts							Naidin *et al.*, 1984a, 1984b; Akimets *et al.*, 1991		Koch, 1977	Schönfeld, 1990
m_2		m_2	m_2^2	*Hanzawaia ekblomi/Pseudotextularia elegans*		BF13	*Pseudotextularia elegans*	XXVI	*Pseudotextularia elegans*	*Pseudotextularia elegans* – I., Zone
			m_2^1	*Gavelinella danica/Brotzenella praeacuta*		BF12	*Brolizwnella praeacuta*	XXV	*Gavellnella danica*	
m_1	m_1^3	m_1	m_1^2	*Bolivinoides draco draco*		BF11	*Bolivinoides draco draco*	XXIV	*Bolvinoides draco draco*	*paleocenicus/reticulata* R.R. Zone
	m_1^2			*Bolivinoides paleocenicus/Neoflaballina reticulata*	*Brolzenella complanata*	BF10b	*Brotzenella complanata*	XXIII	*Neoflabellina reticulata*	
	m_1^1		m_1^1		*Neoflabellina reticulata/Bolivina decurrens*	BF10a	*Angulogavelinella gracilis*	XXII		*decurrens* – I. Zone
cp_3	cp_3^3	cp_2	cp_2^2	*Angulogavelinella gracilis/Bolivinoides peterssoni*		BF9			*Bolivinoides draco miliaris*	*peterssoni/hiltermanni* – C.R. Zone
	cp_3^2			*Neoflabellina praereticulata/Brotzenella taylorensis*	Osanqularia navarroana	BF8b	*Brotzenella taylorensis*	XXI		*navarroana/cristata* – PR. Zone
					Bolivinoides decoratus giganteus	BF8a				
				Bolivinoides draco millaris		BF7	*Bolivinoides draco miliaris*	XX		*miliaris/incrassata* – P.R. Zone
	cp_3^1			*Globoratalites hittermanni (=G. emdyensis)*		BF6	*Cibicidoides voltzianus*	XIX	*Neoflabellina numismalis*	*gracilis* – P.R. Zone
cp_2			cp_2^1	*Brotzenella monterelensis/Heterostomella leopollitana*		BF5	*Brotzenella monterelensis*	XVIII		*leopolitana* – P.R. Zone
cp_1	cp_1^3	cp_1	cp_1^2	*Bolivinoides decoratus decoratus*	*C. volzianus Cibicidoides aktulagagensis/*	BF4c	*Cibicidoides aktulaguensis*	XVII	*Bolivinoides decoratus decoratus*	*laevigatus* – P.R. Zone
	cp_1^2				*Cibicidoides temirensis/ Gavelinella clementiana usakensis*	BF4b	*Cibicidoides temirensis*	XVI		*voltzianus* – P.R. Zone
					Bolivinoides decoratus decoratus/ B. granulatus	BF4a	*Bolivinoides decoratus decoratus*	XV		*granulatus* – P.R. Zone
	cp_1^1		cp_1^1	*Gavelinella clementiana clementiana*		BF3	*Gavelinella clementiana clementiana*	XIV	*Bolivinoides strigillatus*	*wedekindi* – P.R. Zone
				Bolivinoides strigillatus	Stensioeina pommerana	BF2b	*Bolivinoides strigillatus*	XIII		*clementiana* – P.R. Zone
					Gavelinella stelligera	BF2a				*concinna* – I. Zone
										pommerana/frankel – P.R. Zone
										strigillatus – P.R. Zone
st_2		st_2		*Stensioeina granulata perfecta*		BF1	*Stensioeina granulata perfecta*	XII	*Stensioeina granulata perfecta*	*perfecta* – P.R. Zone

Characteristic species: *Spiroplectammina rosula, Stensioeina granulata perfecta, S. granulata incondita, Valvulineria mariei, Osangularia whitei whitei, O. whitei polycamerata, O. whitei crassa, Gavelinella* ex gr. *stelligera, G. infrasantonica, Cibicides excavatus, Cibicidoides eriksdalensis, Praebulimina ventricosa,* and *Bolivinoides strigillatus* (very rare). The lower boundary corresponds to the first occurrence level of index species and other diagnostic forms, and the upper one is established at the disappearance level of *Gavelinella infrasantonica, Gavelinella* ex gr. *stelligera, Cibicides excavatus,* and *Cibicidoides eriksdalensis.*

We subdivided the *Bolivinoides strigillatus* Zone BF2 distinguished by Koch (1977) into the lower *Gavelinella stelligera* BF2a and upper *Stensioeina pommerana* BF2b subzones.

Gavelinella stelligera Subzone BF2a

The *G. stelligera* Subzone was originally recognized by Vasilenko (1961). Later on, its range was changed, because an upper part was distinguished as *Gavelinella clementiana clementiana* Zone (Akimets *et al.*, 1979).

Characteristic species: *Ataxophragmium orbignynaeformis, Gavelinella stelligera, Bolivinoides strigillatus* (common), *Stensioeina pommerana* (rare or single), and *Globotruncana arcaformis.* The lower boundary is established at the first occurrence level of index species and other diagnostic forms, and the upper one corresponds to the disappearance level of the *Osangularia whitei* group.

The *Stensioeina pommerana* Subzone BF2b characterizes the association of newly appearing *Neoflabellina rugosa, Globigerinelloides asper,* and *G. clavatus* with constantly occurring *Stensioeina pommerana.* Almost all species of the previous assemblage occur in this subzone. Its lower boundary marks the first occurrence of *Neoflabellina rugosa* and a sharp abundance growth of *Stensioeina pommerana.* The upper one underlies the distribution range of a new assemblage.

Gavelinella clementiana clementiana Zone BF3.

Akimets *et al.*, 1979 (= upper beds of *Gavelinella stelligera* Zone s.l. after Vasilenko, 1961). The beds were ranked as a zone by Akimets (1980).

Characteristic species: *Orbignyna variabilis, Voloshinovella laffittei, Gaudryina rugosa, Dorothia pupoides, Neoflabellina rugosa, N. wedekindi, N. asema, Eponides concinnus, Gavelinella dainae, G. santonica, Reussella pseudospinulosa, Pyramidina triangularis, Bolivinoides laevigatus finitima,* and *Pullenia dampelae,* which are newcomers and associate with *Bolivinoides strigillatus, Stensioeina pommerana, Globigerinelloides asper, G. clavatus,* and other species inherited from the previous assemblage.

The lower boundary marks the appearance level of newcomers and index species. *Bolivinoides strigillatus* and *Gavelinella santonica* become extinct near the upper boundary.

Bolivinoides decoratus decoratus Zone BF4

Vasilenko (in Trifonov and Vasilenko, 1963).

Characteristic species: *Orbignyna irreperta, Plectina convergens, Osangularia cordieriana, Cibicidoides temirensis, C. aktulagayensis, Bolivinitella galeata, Bolivinoides decoratus decoratus,* and *B. granulatus.* The lower boundary is established at the first occurrence level of index species and associated characteristic forms. The lower one marks disappearance level of several species belonging to *Orbignyna, Gavelinella,* and *Bolivinoides* genera. The zone is subdivided into three subzones.

Bolivinoides decoratus decoratus/B. granulatus Subzone BF4a.

Characteristic species: *Orbignyna irreperta, Eponides moskvini, Osangularia cordieriana, Gavelinella clementiana pseudoexcolata, Bolivinoides decoratus decoratus,* and *B. granulatus.*

Cibicidoides temirensis/Gavelinella clementiana usakensis Subzone BF4b.

Characteristic species: *Gavelinella clementiana usakensis, Eponides biconvexus, Cibicidoides montanus, C. temirensis, Bolivinoides laevigatus laevigatus,* and *Bolivinitella galeata.*

Cibicidoides aktulagayensis/C. voltzianus Subzone BF4c.

Characteristic species: *Spiroplectammina lingua, Arenobulimina vialovi, Heterostomella praefoveolata, Plectina convergens, Orbignyna irreperta, O. simplex, O. inflata, Osangularia cordieriana, Gavelinella bistellata, Brotzenella insignis, Cibicidoides aktulagayensis,* and *C. voltzianus.*

Brotzenella monterelensis/Heterostomella leopolitana Zone BF5.

Characteristic species: *Arenobulimina puschi, Orbignyna inflata, Voloshinovella laffittei, Heterostomella leopolitana, H. praefoveolata, Neoflabellina numismalis, Brotzenella monterelensis, B. menneri,* and *Gavelinella clementiana usakensis.* The lower boundary is established at the appearance level of index species and associated forms. The upper boundary marks disappearance of *Orbignyna variabilis, Brotzenella insignis, Bolivinitella galeata,* and *Praebulimina ventricosa.*

Globorotalites hiltermanni (= *G. emdyensis*) Zone BF6.

The *Globorotalites emdyensis* Zone was originally distinguished by Akimets (1974).

Characteristic species: *Plectina ruthenica, Heterostomella foveolata, Globorotalites hiltermanni* (= *G. emdyensis*), *Stensioeina beccariiformis, Gavelinella clementiana laevigata,* and *Cibicidoides voltzianus.* The lower boundary marks the appearance level of index species and associated characteristic forms, and the lower one corresponds to the disappearance level of *Arenobulimina puschi* and *Gavelinella clementiana pseudoexcolata.*

Bolivinoides draco miliaris Zone BF7.

The zone is established by Koch (1977).

Characteristic species: *Heterostomella gracilis, Neoflabellina buticula, Eponides frankei, E. conspectus, Gavelinella cayexi mangyshlakensis, Gemellides orcinus, Bolivinoides decoratus dracoformis*, and *B. draco miliaris*. The lower boundary marks the appearance level of index species and associated forms. The upper boundary corresponds to the disappearance level of *Gavelinella clementiana pseudoexcolata* and *G. clementiana usakensis*.

Neoflabellina praereticulata/Brotzenella taylorensis Zone BF8.

Characteristic species: *Osangularia navarroana, Neoflabellina praereticulata, Brotzenella taylorensis, Bolivina incrassata incrassata, Bolivinoides decoratus giganteus*, and *Pseudouvigerina cristata*. The lower boundary marks the first occurrence level of index species and other indicative forms.

The zone is subdivided into the lower *Bolivinoides decoratus giganteus* Subzone BF8a, where its index species coexists with *Bolivina incrassata incrassata*, and the upper *Osangularia navarroana* Subzone BF8b that includes, in addition to its index species, *Neoflabellina praereticulata, Pseudouvigerina cristata*.

Anqulogavelinella gracilis/Bolivinoides peterssoni Zone BF9.

Characteristic species: *Neoflabellina praereticulata, Gyroidinoides globosus, Angulogavelinella gracilis, Osangularia navarroana, Bolivinoides delicatulus, B. peterssoni, Pseudouvigerina cristata*, and *Reussella szajnoche*. The lower boundary is placed at the appearance level of zonal and associated species, and the lower one marks the disappearance level of smaller *Brotzenella taylorensis, Gemellides orcinus, Reussella pseudospinulosa*, and some other forms.

Bolivinoides paleocenicus/Neoflabellina reticulata Zone BF10.

In addition to index species, characteristic taxa of the zone are *Gaudryina pyramidata, Anomalinoides subcarinatus, Cibicidoides bembix*, and *Bolivina incrassata crassa*. The mass abundance of *Angulogavelinella gracilis* is also recorded in this interval. The lower boundary corresponds to the appearance level of zonal and other characteristic species. We established two subzones within this unit.

The lower *Neoflabellina reticulata/Bolivinoides decurrens* Subzone BF10a characterizes the distribution interval of both index species in association with *Spiroplectammina suturalis, Bolivinoides paleocenicus, Cibicidoides bembix*, and *Reussella cimbrica*.

The upper *Brotzenella complanata* Subzone BF10b corresponds to the synonymous zone originally established in the East European platform by Grigyalis *et al.* (1974). Later on, stratigraphic range of the zone was changed (Akimets *et al.*, 1983).

Characteristic species: *Gavelinella welleri, Brotzenella complanata, Anomalinoides subcarinatus, Coleites crispus, Bolivina incrassata crassa*, and *Stensioeina praecaucasica*.

Bolivinoides draco draco Zone BF11.

The zone is established by Koch (1977).

Characteristic species: *Spiroplectammina suturalis, Gavelinella midwayensis, Coleites crispus*, and *Bolivinoides draco draco*. The lower boundary marks the appearance level of zonal and other characteristic species, and the upper one corresponds to the disappearance level of *Gavelinella cayexi mangyshlakensis* and *Bolivinoides delicatulus*.

Gavelinella danica/Brotzenella praeacuta Zone BF12.

Characteristic species: *Orbignyna lepida, Gavelinella pertusa, G. danica, Brotzenella praeacuta, Cibicides kurganicus, Anomalinoides pinguis, Reussella minuta, R. cimbrica*, and *Tappanina selmensis*. The lower boundary is established at the first occurrence level of both index species and associated diagnostic taxa. The upper boundary marks disappearance level of *Brotzenella complanata* and some other species.

Hanzawaia ekblomi/Pseudotextularia elegans Zone BF13.

Characteristic species: *Alabamina toulmini, Rosalina binkhorsti, Hanzawaia ekblomi, Cibicides clipeatus, Karreria fallax*, and *Pseudotextularia elegans*. The lower boundary is placed at the first occurrence level of index species and associated taxa, and the upper one corresponds to the boundary between the Cretaceous and Paleogene systems. This one marks significant changes in specific and generic compositions of many foraminiferal groups.

RANGES OF ZONES AND SUBZONES

According to Naidin (1995, p. 52, Fig. 2), the late Santonian–Maastrichtian interval is 19.5 m.y. long. Zones described above have highly variable ranges. Those with short-term ranges are concentrated near the Santonian–Campanian and Campanian–Maastrichtian boundaries (Fig. 4). For instance, ten zonal units are distinguished in the upper Santonian–Campanian interval (7 m.y. according to the time scale by Naidin). The Santonian–Campanian and Campanian–Maastrichtian boundary periods corresponded to commencement and termination of transgressive–regressive cycles. Zones of longer duration (from about 1.5 to 3 m.y.) corresponded to phases of the basin stabilization (middle–late Campanian and Maastrichtian). Reorganization periods, such as commencement and termination of transgressive–regressive cycles, were marked by activated phylogenetic evolution of benthic foraminifers. Using data on northwestern Germany, Schoenfeld (1990) established that abundance peaks of newly appeared species (up to 25 specimens per 1 m.y.) coincide with great regressions in the initial late Santonian

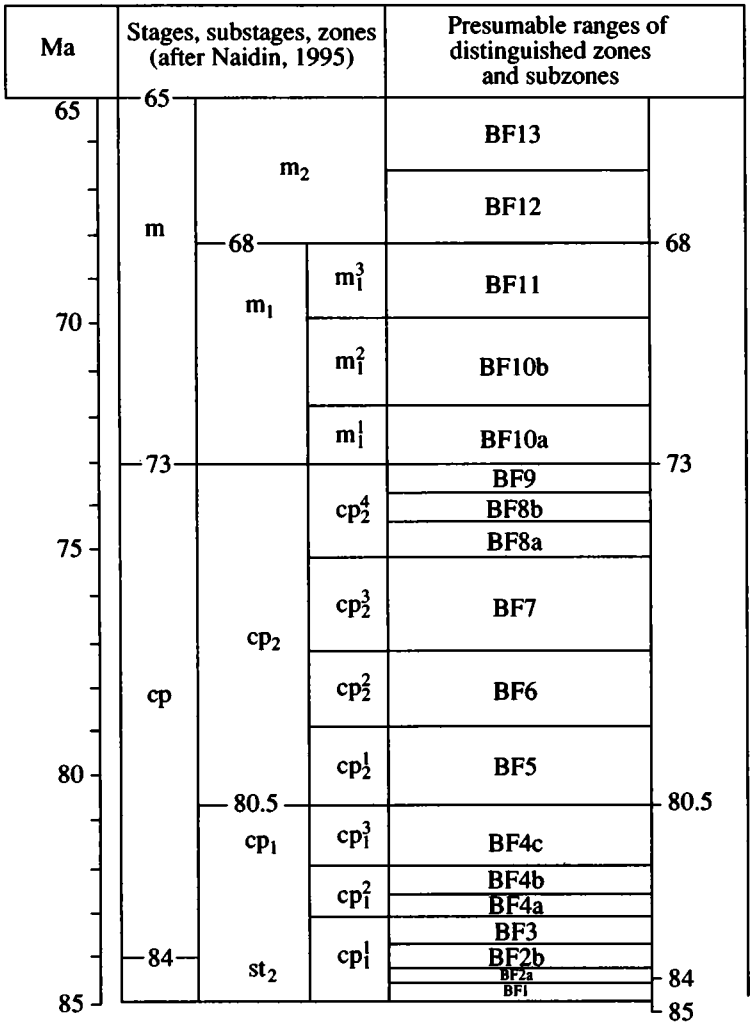


Fig. 4. Time ranges of biostratigraphic units.

and during terminal phases of the early and late Campanian.

Grigyalis *et al.* (1980) were first to use phylogeny as a basis for the Upper Cretaceous foraminiferid zonation in the East European platform. Following them, we used phylogenetic lineages of genera *Orbignyna, Voloshinovella, Heterostomella, Globorotalites, Stensioeina, Neoflabellina, Gavelinella, Brotzenella, Cibicidoides, Bolivina*, and *Bolivinoides* in our zonation of the upper Santonian–Maastrichtian of the EPR (Fig. 5, Plate).

Phylogenetic lineages of *Neoflabellina, Gavelinella, Osangularia*, and *Stensioeina* continue into the late Santonian–early Campanian, when phylogeny of the genus *Bolivinoides* began. Phylogenetic lineage of the latter: *B. laevigatus* (late Santonian–early Campanian)—*B. decoratus decoratus* (early–late Campanian)—*B. australis* = (*B. decoratus dracoformis* ?), *B. draco miliaris, B. decoratus giganteus* (late Campanian–early Maastrichtian)—*B. draco draco* (terminal early Maastrichtian), is recorded in different areas of the globe. Petters (1977) reported on the following zones of this genus: (1) *Bolivinoides strigillatus* Zone of the upper Santonian–lower Campanian in Australia, North America, and Europe; (2) *Bolivinoides decoratus decoratus* Zone of the Campanian in America, Europe, and North Africa; (3) *Bolivinoides draco miliaris* Zone of the upper Campanian–lower Maastrichtian in North America and Europe; (4) *Bolivinoides draco draco* Zone of the middle–upper Maastrichtian in Europe, Middle East, North Africa, and Australia. *Bolivinoides draco draco* is a cosmopolitan species characteristic of Maastrichtian deposits in the Atlantic outer shelf and bathyal zones (Markhoven *et al.*, 1986).

The evolutionary appearance of *Cibicidoides temirensis* characterizes the mid-early Campanian. By the end of the early Campanian, this form was replaced by *C. aktulagayensis* (= *involutus*) and *C. voltzianus*. The

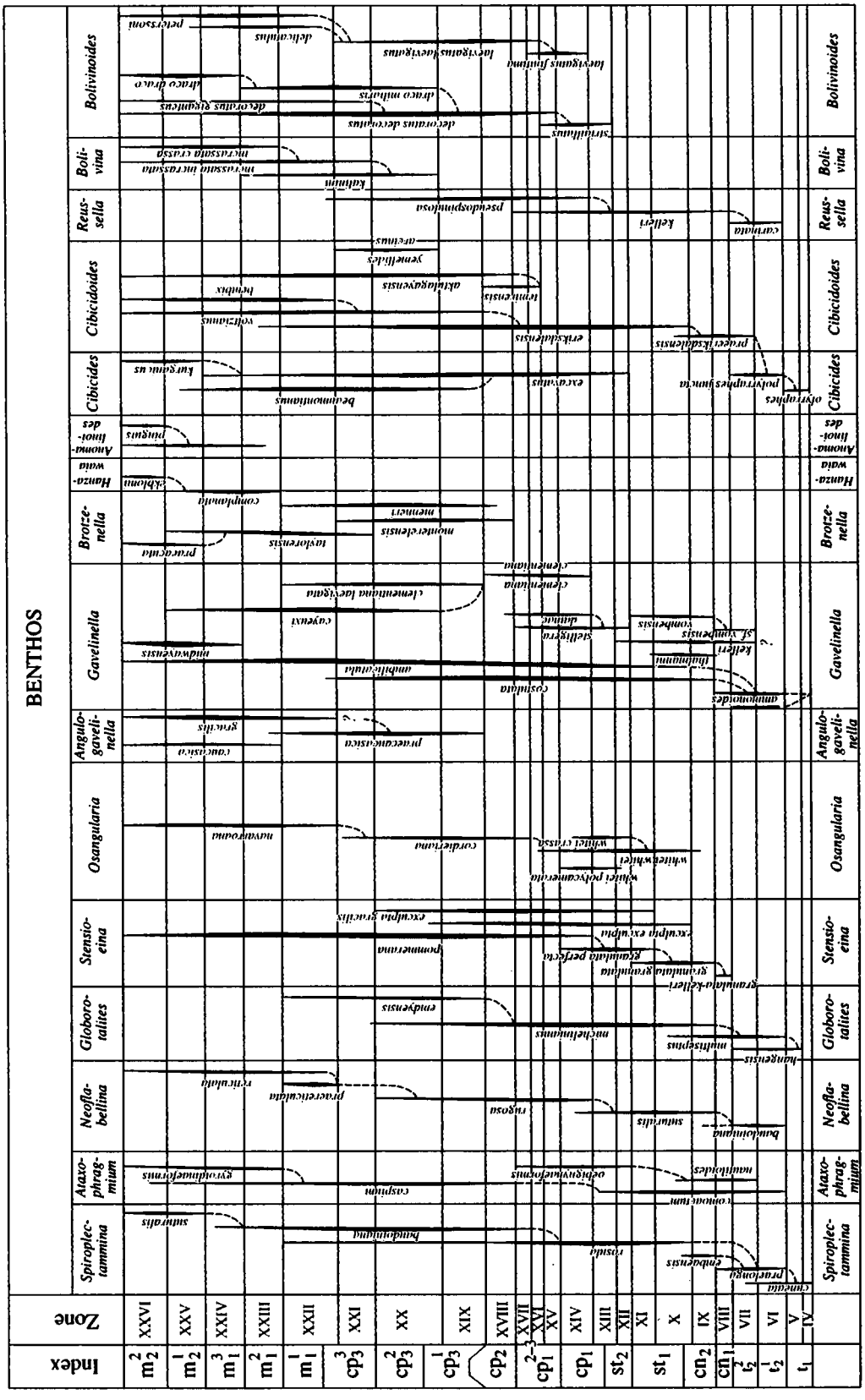
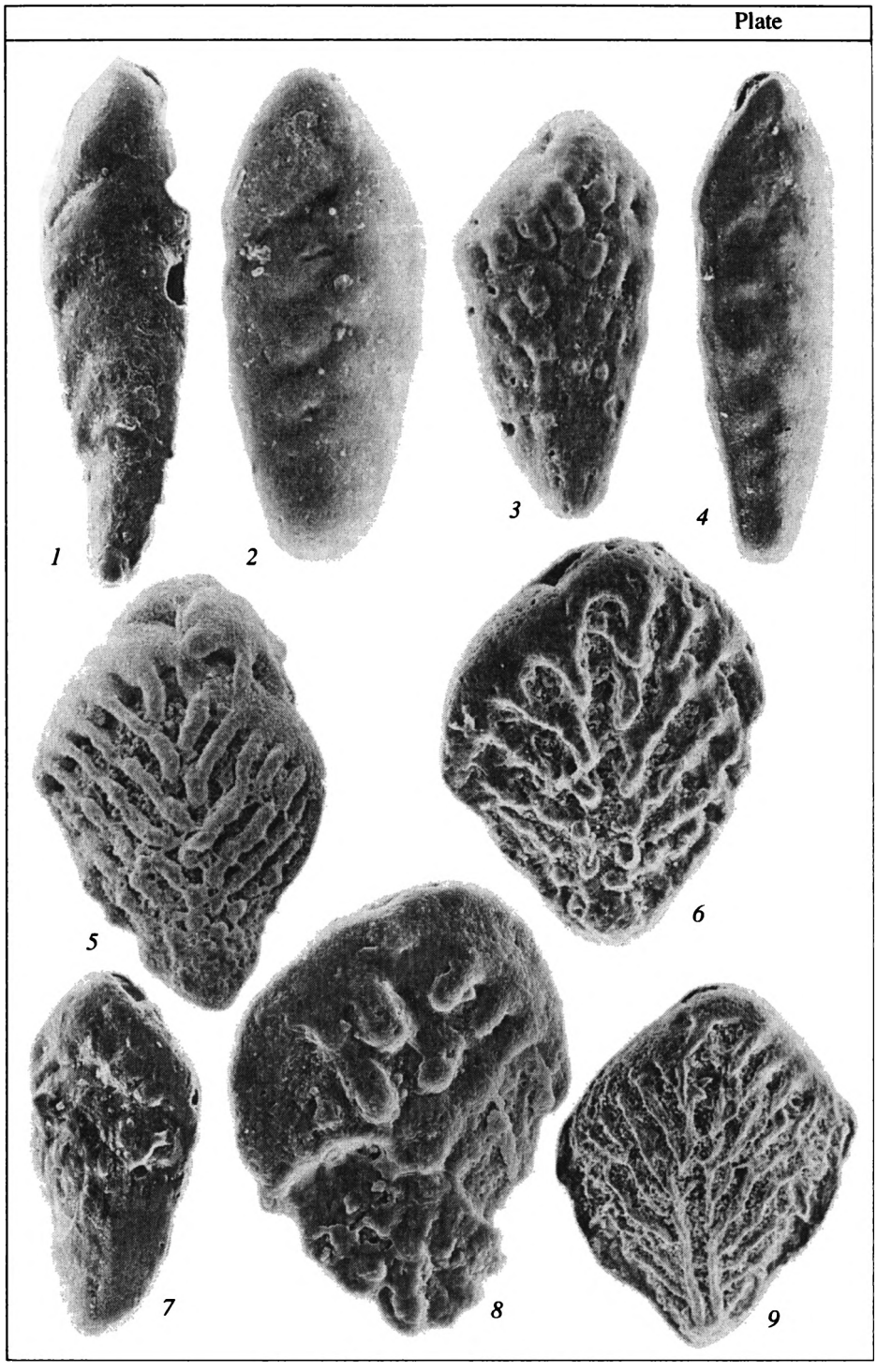


Fig. 5. Phylogenetic lineages of characteristic Late Cretaceous genera of benthic foraminifers in the eastern EPR.



Bolivina and *Bolivinoides* forms from the upper Santonian–Maastrichtian of the EPR.

(*1*) *Bolivina decurrens* Ehrenberg, Sample 68/73, Peri-Caspian, upper Maastrichtian, ×160. (*2*) *Bolivina incrassata crassa* Vasilenko, Sample 68/88, Peri-Caspian, upper Maastrichtian, ×140. (*3*) *Bolivinoides decoratus decoratus* (Jones), Sample 68/348, Peri-Caspian, lower Campanian, ×140. (*4*) *Bolivina incrassata incrassata* Reuss, Sample 68/142, Peri-Caspian, upper Campanian, ×80. (*5*) *Bolivinoides giganteus* Hiltermann et Koch, sample 68/131, Peri-Caspian, upper Campanian, ×140. (*6*) *Bolivinoides draco miliaris* Hiltermann et Koch, Sample 68/150, Peri-Caspian, upper Campanian, ×190. (*7*) *Bolivinoides laevigatus* Matie, Sample Ak/10-16, Mangyshlak, lower Campanian, ×160. (*8*) *Bolivinoides peterssoni* Brotzen, Sample Ak/14-8, Mangyshlak, lower Maastrichtian, ×300. (*9*) *Bolivinoides draco draco* Marsson, Sample 68/97, Peri-Caspian, lower Maastrichtian, ×110.

latter is the ancestral form in the lineage *C. voltzianus—C. bembix—C. succedens.*

Phylogeny of the genus *Brotzenella* takes origin in the middle Campanian. The evolutionary appearance of *B. monterelensis* distinctly marks the upper boundary of the lower Campanian not only in the eastern EPR, but also in the Mons basin (Robaszynski and Christensen, 1989) and in the Campanian Stage stratotype (Plattel, 1977). Evolutionary changes in ornamentation of umbilical knobs and thickening of inner ends of septal sutures is clearly visible in the *Brotzenella* lineage *B. monterelensis—B. taylorensis—B. complanata—B. praeacuta—B. acuta—B. discoids—B. turkmenica—B. taurica.*

The peak phylogenetic evolution of all genera was in the late Campanian. This was a period of evolutionary appearance of the genus *Gemellides* that is genetically interrelated with the late Maastrichtian genus *Hanzawaia.* Species *H. ekblomi* of the latter was the ancestral form of the Paleogene lineage *H. ekblomi—H. montaensis—H. ammophilla.* The *Bolivina* phylogenetic lineage *B. kalinini—B. incrassata incrassata—B. incrassata crassa (= gigantea)*, in which tests become progressively more massive with thicker walls, also takes origin in the late Campanian. *Bolivina incrassata* is a cosmopolitan form widespread in the upper Campanian–Maastrichtian deposits of Europe, North America, and oceans (Markhoven *et al.*, 1986).

A gradual decline of phylogenetic evolution took place during the Maastrichtian. In the Peri-Tethys, Danian and Maastrichtian assemblages have only few species in common: *Brotzenella praeacuta, Hanzawaia ekblomi, Gavelinella welleri*, and *Karreria fallax.*

Some Important Feature of Foraminiferid Distribution in the Eastern and Western EPR

Figure 6 shows that zonal assemblages include three groups of foraminifers.

Group A. These are taxa widespread everywhere. They are represented by three types of species: (1) by those having identical stratigraphic ranges; (2) by forms of synchronous appearance, but asynchronous disappearance; and (3) by species of asynchronous appearance. Among the latter, there are forms appearing in the east of the EPR earlier than in the west and forms, which are recorded, in contrast, later in the east than in the west.

For instance, *Bolivinoides laevigatus* appears in the lowermost Campanian of the Mangyshlak basin and only in the initial upper Campanian, i.e., about 3 m.y. later, in northwestern Germany. *Cibicidoides voltzianus* has first occurrence at the initial middle Campanian in the west and appears westward near the base of upper Campanian (about 2 m.y. later).

Group B. Taxa of the group are either much more abundant in the western EPR, or occur in this region only. These are some representatives of genera *Heterostomella, Stensioeina, Bolivinoides*, and *Neoflabellina.*

Group C. This group includes species unknown in the west and typical of the eastern EPR only. These are either zonal index species or characteristic forms of zonal assemblages.

Some of the distinguished zones, e.g., BF5, BF6, and BF10, have two index species, one typical of the western EPR areas and other characteristic of the eastern region.

Paleobiogeographic Subdivision of EPR

Investigating belemnites, Naidin (1973) divided the East European platform into two provinces: the western one that was populated by *Goniotheutis* forms and the eastern province, where these forms are unknown, but *Belemnitella* species are widespread.

Data on foraminifers also allow us to distinguish the West and East European provinces of the EPR (Fig. 1). The latter covered area of the East European platform and western part of the Turan plate.

The West European province is characterized by abundance of foraminiferal species representing Group B: *Neoflabellina wedekindi, N. asema, N. numismalis, N. buticula, Heterostomella gracilis*, and *Bolivinoides paleocenicus*, which are missing from eastern areas. The province had connections with the North Sea and North Atlantic basin, where *Reussella szajnoche* is one of most characteristic benthic forms (King, 1989; Schoenfeld and Burnett, 1991). Its connections with the Tethys were limited however, and planktonic foraminifers are very rare here, so that many sections are barren of these fossils. Another characteristic feature of the province is abundance of tropical orbitoids in Maastrichtian deposits (e.g., the upper Maastrichtian beds of the stratotype section near the town of Maastricht, Holland, are overfilled with these fossils).

The East European province represented area of development of *Orbignyna, Arenobulimina, Marssonella, Voloshinovella, Gavelinella*, and *Brotzenella* genera. Its endemic taxa were *Cibicidoides temirensis, C. aktulagayensis, Gemellides orcinus, Brotzenella menneri, B. taylorensis, Anomalinoides subcarinatus*, and some other species.

The East European province was connected with the boreal West Siberian sea via the Turgai depression and some straits crossing the central Urals (Fig. 7). The former existence of latitudinal Middle Uralian strait was suggested by Papulov (1974). The westernmost exposures of Santonian sediments accumulated in the West Siberian sea are known near the Nizhnii Tagil, only 200 km away from the extreme northern outcrop of deposits of the East European platform near the Krasnoufimsk. Boreal water mass penetrated via the presumable strait from Siberia into the seas of East European province. It was a migration pass of radiolarians and boreal bivalve *Oxytoma (Pteria) tenuicostata*

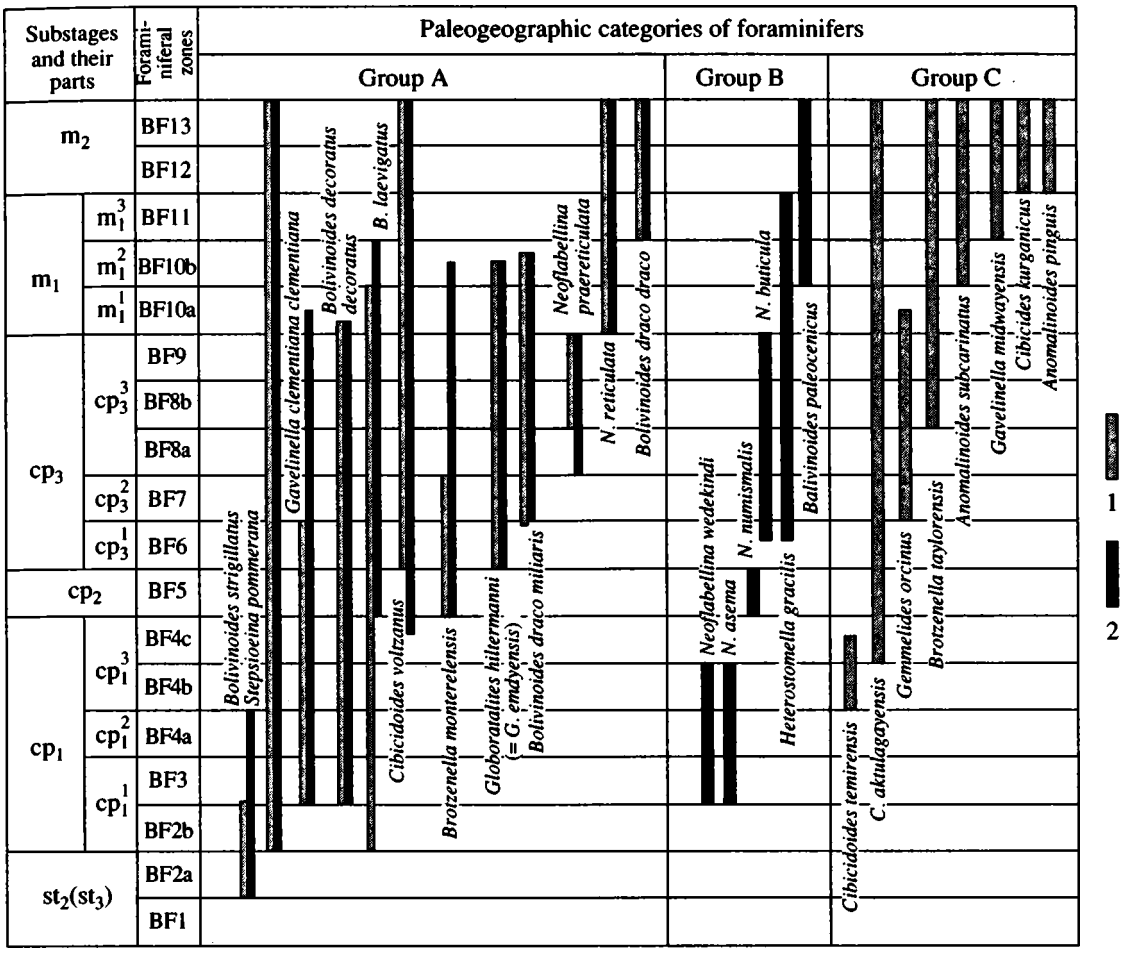


Fig. 6. Three groups of benthic foraminifers from zonal assemblages of the EPR: (1) occur in the east; (2) occur in the west.

(Roemer). Away from the strait site, deposits bearing *O. tenuicostata* become younger. For instance, in close proximity to the strait (the Sengilei site 40 km southward of the town of Ul'yanovsk), first valves of *O. tenuicostata* are found in the lower Santonian beds (Beniamovskii *et al.*, 1988), but in the eastern Peri-Caspian depression their mass accumulations are confined to upper Santonian–lower Campanian deposits; scarce remains of this boreal mollusk are also discovered from lower Campanian beds northward of Donbass (Papulov and Naidin, 1979; Naidin and Ivannikov, 1980). The Santonian and Campanian siliceous sediments bearing radiolarians are widespread in the west of the Peri-Caspian syneclise along the right side of the Volga River, from Ul'yanovsk to its lower reaches. Gerasimov *et al.* (1962) assumed that there was a strong northern current that promoted migration of radiolarians to the south. This is one more argument in favor of former existence of the Middle Uralian strait that connected the East European basin of the Peri-Tethys with the boreal West Siberian sea. The strait presumably existed till the end of the Campanian (Amon *et al.*, 1997; Amon, 2001). Dark carbonate-free siliceous clay and opoka beds of the Santonian–upper Campanian interval that were penetrated by a borehole near the Volgograd yield abundant radiolarians, among which there are many species known from the West Siberian basin (Bragina *et al.*, 1999).

The Turgai strait was in action since the mid-Campanian time, as it is evident from distribution of foraminifers in the Santonian–Maastrichtian deposits of the northern Turgai depression and adjacent Trans-Uralian areas (data of Amon in *Verkhnemelovye...* 1990). The Santonian and early Campanian foraminiferal assemblages consist entirely of boreal benthic species, which have sandy walls and West Siberian origin. Dominant among them were representatives of Lituolida, Astrorhizida, and Ammodiscida orders, which associated with trochamminids and scarce ataxophragmiids (8%). Since the mid-Campanian time, taxonomic composition of foraminiferal assemblages changed: abundance of lituolids, astrorhizids, and ammodiscids decreased, but representatives of ataxophragmiids became more abundant (21%), and secretory rotaliids

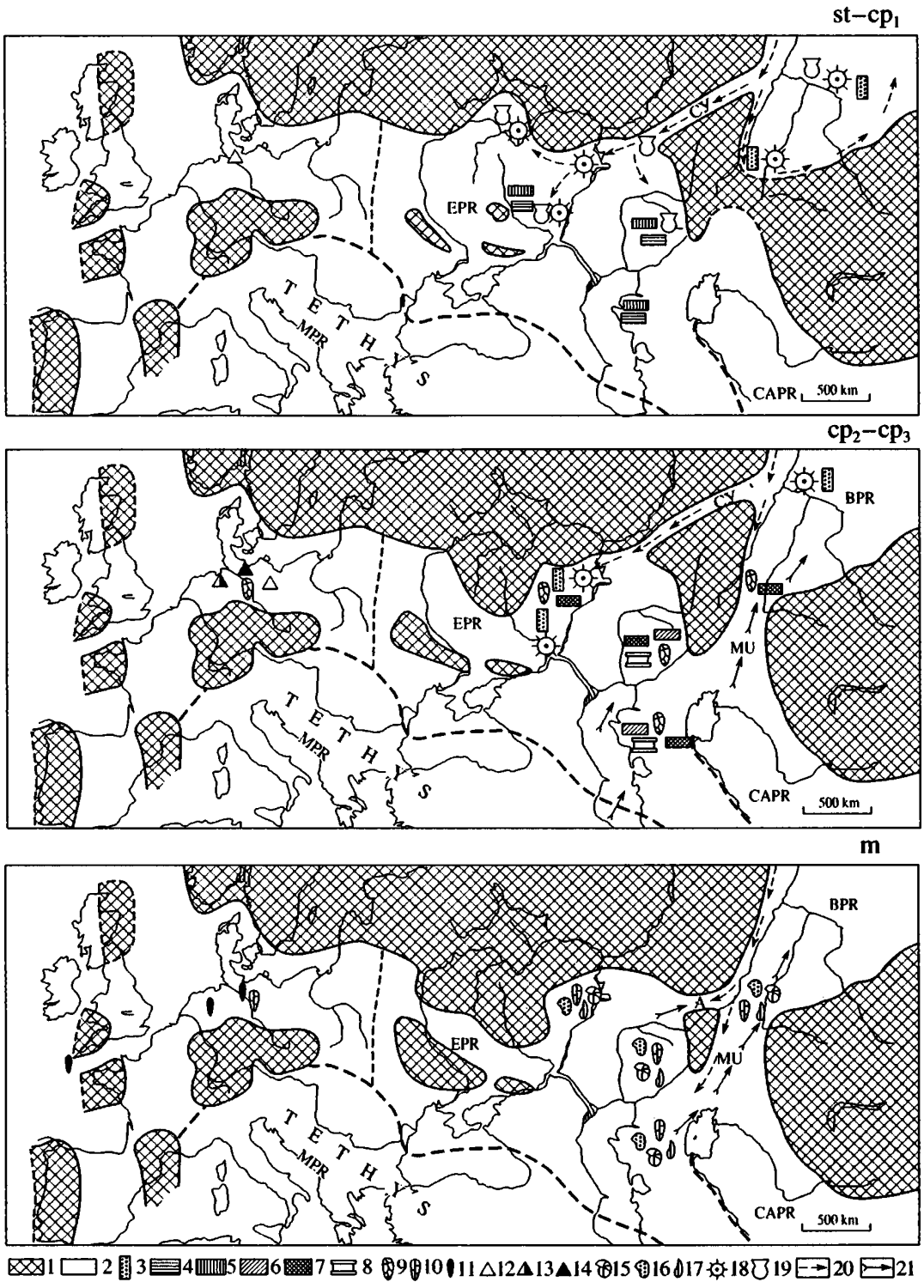


Fig. 7. Distribution of some characteristic late Santonian–Maastrichtian benthic foraminifers in the EPR seas, West Siberian basin of the Boreal paleobiogeographic region (BPR), and Turgai seaway (T): (1) land; (2) sea; (3) *Bathysiphon nodosariiformis*; (4) *Cibicidoides temirensis*; (5) *C. aktulagayensis*; (6) *Gemellides orcinus*; (7) *Brotzenella taylorensis;* (8) *Globotruncana morozovae*; (9) *Bolivina kalinini*; (10) *Bolivinoides draco draco*; (11) *B. paleocenicus*; (12) *Neoflabellina wedekindi;* (13) *N. leopolitana*; (14) *N. gracilis*; (15) *Anomalinoides subcarinatus*; (16) *A. pinguis*; (17) *Cibicides kurganicus*; (18) Radiolaria; (19) *Pteria tenuicostata*; (20) species migration from West Siberian basin in the EPR; (21) species migration in opposite direction; (CAPR) Central Asian paleobiogeographic region; (MPR) Mediterranean paleobiogeographic region; (MU) Middle Uralian strait; (A) Ayat strait.

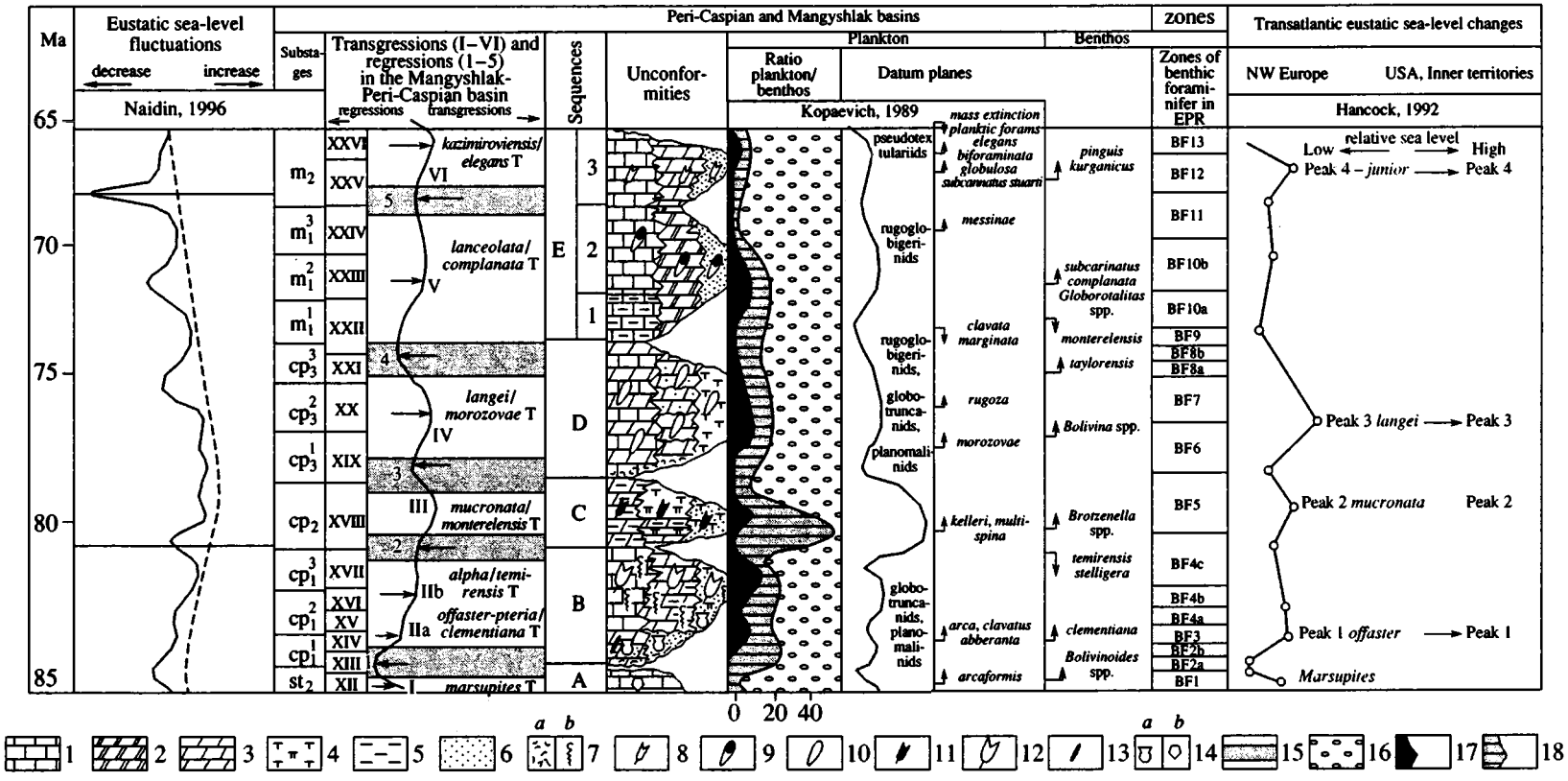


Fig. 8. Eustatic transgressions and regressions of the late Santonian–Maastrichtian time: (1) chalk; (2) chalk-like marl; (3) marl; (4) calcareous clay; (5) clay; (6) sand; (7) phosphorite (*a*) and bioturbation (*b*); (8) *Neobelemnella kazimiroviensis*; (9) *Belemnella lanceolate*; (10) *Belemnitella langei*; (11) *B. mucronata mucronata*; (12) *B. mucronata alpha*; (13) *Actinocamax laevigatus*; (14) *Pteria tenuicostata* (*a*) and *Marsupites testidinarius* (*b*); (15) regression phase; (16) benthic foraminifers; (17) keeled planktonic foraminifers; (18) keel-free planktonic foraminifers.

appeared at that time (21%). Abundance of European species also grew since the middle Campanian (their abundance rate was 30% in the middle Campanian and 55% by the end of the Maastrichtian). Taxonomic composition of assemblages from the northern Turgai area completely changed in the terminal Campanian: agglutinated lituolids, astrorhizids, ammodiscids, and trochamminids became extinct giving place to dominant secretory rotaliids; abundance of planktonic forms became as high as 18%. Some Senonian West Siberian species, such as *Cibicides kurganicus, Anomalinoides subcarinatus*, and *A. pinguis*, which are present in the Maastrichtian deposits of the eastern EPR, suggest that migration via the Turgai strait developed in northern and southern directions. Boreal *Anomalinoides pinguis* reached the sea basin of Poland, where it is distinguished as an index species of the upper Maastrichtian (Gawor-Biedowa *et al.*, 1984). In addition to the Turgai strait that was principal one during the Maastrichtian, there was the Ayat strait located between the Urals and Mugodzhary Mountains (Amon *et al.*, 1997). Influence of the latter is evident from the fact that identical foraminiferal zones XXII–XXVI, as well as *Belemnitella lanceolate* and *Neobelemnella kazimiroviensis* zones of the Maastrichtian, are distinguished in two sites located 150 km away from each other, namely in the Orsk graben of the southern Urals and in the Ayat River sections of the southern Trans-Urals. Amon (1998, and data in *Verkhnemelovye...* 1990) who compared zonal scales for the eastern EPR, northern Turgai depression, and West Siberia came to the conclusion that they can be easily correlated beginning since the late Campanian, and that the upper Maastrichtian zonations suggested for the Turgai depression and eastern EPR are merely identical.

The epicontinental basin of the East European province was actually the periphery of the Tethys. Planktonic foraminifers, though not as abundant and diverse as in the latter, persistently occur in this province, especially in its southern Crimea–Caucasus area (Maslakova, 1978). Abundance of planktonic foraminifers grew up to 50–60% during the periods of transgressions, when the deep-water keeled *Gobotruncana* and keel-free *Rugoglobigerina* forms migrated into the epicontinental basin (Kopaevich, 1989). In shallow zones and during the regressive phases, abundance of planktonic taxa was insignificant (locally they were absent). These were mostly planomalinids and scarce underdeveloped globotruncanids. Five transgressive–regressive cycles are distinguished in the upper Santonian–Maastrichtian deposits of the Mangyshlak–Peri-Caspian basin (Fig. 8) on the basis of lithological complexes separated by hiatuses in shallow-water sections and marked by appearance of characteristic planktonic foraminifers. Evolution of some benthic foraminifers, mollusks, and other faunal groups is also interrelated with these cycles. The cycles are of the eustatic origin, as they are correlative with sea-level fluctuation patterns in southwestern Europe and the United States (Hancock, 1992).

CONCLUSION

(1) The suggested zonation of late Santonian–Maastrichtian benthic foraminifers is based on the analysis of zonal schemes elaborated for different EPR areas, among which those of the Mangyshlak–Peri-Caspian region and northwestern Germany were of prime significance.

(2) This detailed zonation includes 18 biostratigraphic units (13 zones and 5 subzones). Its precision is higher than in previous zonation elaborated for the eastern EPR and verifies position of the Santonian–Campanian and Campanian–Maastrichtian boundaries.

(3) Nearly all zones can be widely used in practice. They are traceable in different areas of the EPR and outside the latter, in the Middle East, North America, North Africa, Australia, and oceans.

(4) The benthic foraminifer zonation is 2–3 times more detailed than that of planktonic forms.

(5) The distinguished zones are variable in ranges. Those of narrow stratigraphic intervals are recognized close to the Santonian–Campanian boundary and in the terminal Campanian. They correspond to initial and terminal phases of transgressive–regressive cycles, which accelerated evolution of benthic foraminifers.

(6) Phylogeny of genera *Heterostomella, Neoflabellina, Stensioeina, Globorotalites, Gavelinella, Brotzenella, Cibicidoides, Bolivina, Bolivinoides*, and some others is a basis of the suggested scheme. The isochronous appearance and distribution of some stratigraphically important species representing genera *Stensioeina, Bolivinoides*, and *Bolivina* are traceable not only in Europe, but also in other continents and oceans.

(7) We suggest to distinguish three substages in the Campanian Stage instead of two, as is now authorized, because of a long duration of the stage (11 m.y.). The lower Campanian should correspond to the evolutionary phase of belemnites *Goniotheutis* ex gr. *quadrata, Actinocamax laevigatus*, and *Belemnitella* ex gr. *langei* associated with first *Belemnitella mucronata* (e.g., *mucronata alpha*). The middle substage can be considered as spanning the range to the *Belemnitella mucronata* Zone that corresponds to the first occurrence level and further evolution of benthic foraminifers of the *Brotzenella monterelensis* Zone. It is reasonable to begin the upper Campanian from the first occurrence level of *Belemnitella* ex gr. *langei*, and this substage would be identical to zones BF6–BF9 of benthic foraminifers. As a result, the Campanian would be divided into the natural evolutionary phases of belemnites and foraminifers.

(8) According to geographic and biostratigraphic ranges of benthic foraminifers, the EPR can be divided into its western and eastern provinces. The former was connected with the North Sea and North Atlantic basin, and the latter had connections with the Tethys and boreal West Siberian sea, in the last case via the Middle Uralian strait during the Santonian and early Campa-

nian and via the Turgai strait since the middle Campanian. The Middle Uralian strait closed in the Maastrichtian, when seas remained to be connected via the Turgai and new South Uralian straits. This event resulted in disappearance of radiolarians from Maastrichtian deposits of the Eastern province and in simultaneous abundance growth of European foraminifers in the Trans-Uralian assemblages.

(9) Various events, such as appearance of stratigraphically important species of benthic and planktonic foraminifers, alternation of lithological facies, and breaks in sedimentation, were interrelated with eustatic transgressive–regressive cycles. Six cycles of this kind are distinguished in deposits of the Mangyshlak–Peri-Caspian basin, and their synchronous counterparts are traceable in Western Europe and North America.

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Palynological Characteristics of Paleocene Deposits in the Lower Volga Region (Borehole 28, Town of Dubovka)

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Abstract—Assemblages of organic-walled phytoplankton from Paleocene deposits of the Volga lower reaches are analyzed. Five palynological assemblages distinguished in the borehole section are well correlative with those from coeval deposits of Denmark and Belgium. A break in sedimentation spans the late Danian–early Selandian interval at the boundary between the lower and upper Syzran' subformations.

Key words: Lower Volga region, Paleocene, marine deposits, organic-walled phytoplankton, spores, pollen, palynological assemblage.

INTRODUCTION

Study on Paleogene deposits in the Volga River region was initiated by A.P. Pavlov in 1896 and continued by many geologists (Arkhangel'skii, 1928; Milanovskii, 1940; Brazhnikov *et al.*, 1959; and others). A complex geological structure of these deposits poor in paleontological remains necessitates comprehensively description of stratigraphic units established here. Leonov (1961) divided the Paleogene sequence of the Volga River lower reaches into the Berezina Beds, Syzran', Kamyshin and Proleika formations replacing one another from the base upward.

The Berezina Beds are represented by fine-grained quartz–glauconite sands (up to 6 m thick). The beds rest on the erosional surface of Upper Cretaceous deposits and underlie the Syzran' Formation. At their base, there is a bed of phosphorite pebblestone about 1.5 m thick that contains rounded remains of shark teeth, coprolites, and fragmented oyster shells. Age of the beds has not been established.

The Syzran' Formation overlies with evident hiatus either the Berezina Beds, or the eroded surface of Upper Cretaceous deposits. The formation is of two-member structure. The lower Syzran' Subformation is composed of dark gray to bluish and yellowish opokas (up to 80 m thick). Its scarce fauna includes single pelecypods, corals, and large poorly preserved rhizopods. Musatov (1993) established that the nannoplankton assemblage of the unit is characteristic of the *Coccolithus robustus* Subzone (NP4).

Opokas grade upward into gray to yellowish clayey glauconite sandstones of the upper Syzran' Subformation (up to 70 m thick) containing abundant pelecypods and gastropods. Bun-shaped concretions of compact calcareous sandstones at the subformation base are overfilled with pelecypod and gastropod shells. This basal horizon marks the boundary between the lower and upper Syzran' subformations. The most frequent fossils are *Ostrea sinzowi* Netsch., *Turritella kamyschinensis* Netsch., *T. leymeriei* Netsch., *Volutilithes elevatus* Sow., *Nucula bowerbanki* Sow., *Crassatella stuckenbergi* Netsch., *Cucucllaea volgensis* Barb., *Cyprina morrisi* Sow., and *Corbula volkensis* Arkh. (Zubkovich, 1960). The upper part of the upper Syzran' Subformation is composed of sands with siliceous sandstone interbeds. It yields an impoverished nannoplankton assemblage characteristic of the *Fasciculithus tympaniformis* Zone (NP5) (Musatov, 1993). According to Kuznetsova (1973), a spore–pollen assemblage of the Syzran' Formation is dominated by pollen of gymnosperms (up to 40–60%), especially of pines and cypresses. The assemblage is correlative to that from the El'burgan Horizon of the northern Caucasus.

The basal horizon of the Kamyshin Formation (up to 3 m thick) corresponds to coarse-grained cross-bedded sands and sandstones with well-rounded pebbles and small teeth of sharks and skates. Above it, there are dark gray sandy clays and opokas up to 10 m thick. The upper part of the formation (30 m thick) is represented by structurally complex sequence of quartz sands with clay and sandstone interbeds. The Kamyshin Formation is divided into the lower and upper Kamyshin beds composed of clayey opokas and sands, respectively. The formation is poor in fossils. Conchiofauna is represented by a single species *Teredina* sp. (Zubkovich, 1960). Near the town of Kamyshin, the upper Kamyshin Beds contain leaf imprints studied by many researchers (Pavlov, 1896; Baranov, 1959; Makulbekov, 1977; and others). The corresponding flora is dominated by remains of *Magnolia kamyschinensis* Baranov, *Persea palaeomorpha* Sap. et Mar., *Litsea magnifica* Sap., *Ficus murczisonii* Makul., *Ushia kamyschinesis* (Goepp.) Kolak., *Ushia janischevskii* Makul.,

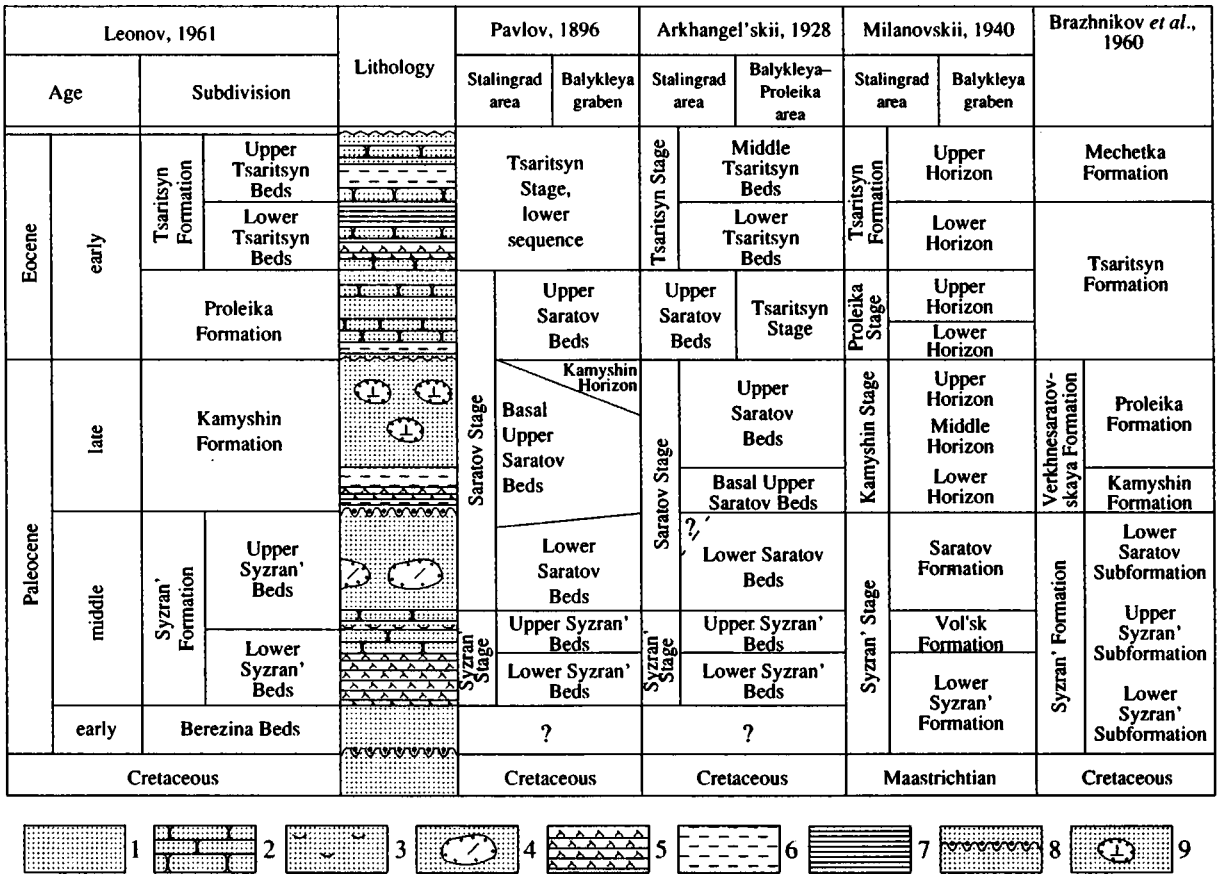

Fig. 1. Composite Paleogene section for the Volga River lower reaches and different versions of its stratigraphic subdivision: (1) sand; (2) predominantly siliceous–clayey sandstone; (3) oyster bed; (4) calcareous concretionary sandstone; (5) opoka; (6) sandy clay: (7) clay; (8) erosional surface; and (9) siliceous concretionary sandstone.

Ushia alnophylla Makul., *Ternstroemiacites sukaczevii* (Baranov) Makul., *Ternstroemiacites palibinii* Makul., *Ilex stenophylla* Ung., *Dewalquea gelindenensis* Sap. et Mar., *Oxycarpia bifaria* Trautsch., and *Posidonia volgensis* Makul. Prevailing in the Kamyshin spore–pollen assemblage (Kuznetsova, 1965, 1970, 1973) is pollen of angiosperms mostly belonging to the "stemma" Normapolles Pflug and including diverse representatives of genera *Trudopollis* Pflug and *Oculopollis* Pflug.

The Proleika Formation (up to 40 m) consists of fine-grained, commonly consolidated clayey quartz–glauconite sands with interbeds of siliceous–clayey sandstones. The interbeds are rare in the upper part of the formation and predominant in the lower one. A member (up to 3 m thick) of sandy opoka, opoka-like sandstones, and sandy clays occurs at the base of the formation. The upper boundary of the formation is marked by a persistent horizon of heterogranular coarse-grained quartz sand with large bright green grains of glauconite. The formation is poorly in paleontological aspect. Morozova (1960) identified single foraminifers *Globorotalia* cf. *crassaeformis, Globigerina* ex gr. *triloba,* and *Cibicides* sp. from the basal bed of conglomerate-like sandstone. The upper part of the formation yields some impressions and casts of pelecypods and gastropods (Semenov and Semenova, 1953; Zubkovich, 1956). The palynological assemblage of the Proleika Formation (Kuznetsova, 1970, 1973) is analogous to the Kamyshin assemblage.

It should be noted that some researchers (Brazhnikov *et al.*, 1960; Distanov and Kuznetsova, 1970; and others) do not accept the subdivision suggested by Leonov (1961) and prefer schemes of Pavlov (1896) and Arkhangel'skii (1928) (Fig. 1). In particular, they divide the Syzran' Formation into three subunits considering the lower part of the Kamyshin Formation as an additional constituent under the name of the lower Saratov Subformation. Such a subdivision principle is not consistent with the Russian Stratigraphic Code. In this case, the rest of the Kamyshin Formation and Proleika Formation are termed as the Verkhnesaratovskaya Formation of Paleocene–Eocene age. According to Zubkovich (1975), the Paleocene deposits of the Saratov–Volgograd area correspond to the Syzran' Group divided into lower (Berezina Beds included) and upper

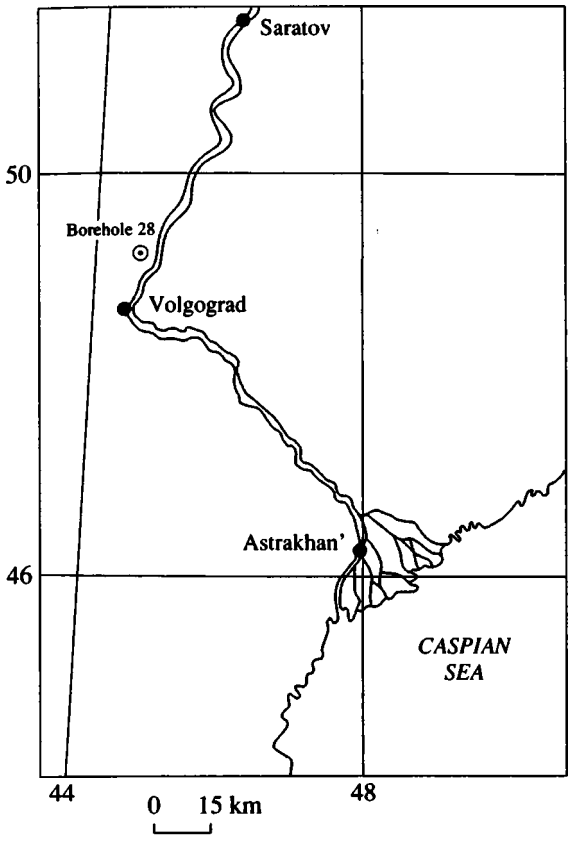

Fig. 2. Location site of Borehole 28.

subgroups, and the Kamyshin Formation. He considers the Proleika Formation as an age equivalent of the lower Eocene Kanev Formation of the Ukraine. In opinion of Kurlaev and Akhlestina (personal communication), the Paleocene is represented by two subformations of the Syzran' Formation (without Berezina Beds) coupled with the Nizhnesaratovskaya Subformation, whereas the Kamyshin and Proleika formations correspond to the Eocene. Thus, the Paleogene stratigraphy in the Volga River lower reaches is unclear so far and inadequately substantiated.

Scarce fossils, facies variability, and repeated occurrence of similar lithological members of the lower Paleogene formations in the Volga region lead to uncertain stratigraphic interpretation. Taking into consideration the conformable occurrence of the lower and upper Syzran' subformations, the latter of which bears the molluscan assemblage similar to the Thanetian assemblages of Western Europe and the Crimea, Leonov (1961) attributed the entire Syzran' Formation to the Thanetian. In the lower Syzran' Subformation of the Middle Volga River middle courses, Kozlova (1983) recognized, however, the beds with radiolarians *Buryella(?) alifera* and abundant diatoms of the *Trinacria heibergiana* Zone (Glezer, 1979), which are correlative to the Danian assemblages of Western Europe. Kuznetsova (1973) correlated palynomorphs of the Syzran' Formation with the Danian–Paleocene palynological assemblages of Central Europe, Belgium, central Kazakhstan and other regions. The age of the Proleika Formation is also a subject of controversy. Leonov (1961) and Zubkovich (1975) dated it back to the Eocene. On the basis of lithological composition and spore–pollen assemblages from the reference sections, Distanov and Kuznetsova (1970) referred the Kamyshin and Proleika formations to a single large sedimentological complex of the Kamyshin time, considering the Proleika Formation as a subunit component of the Kamyshin Formation. According to these authors, the Proleika Formation (as well as the entire Kamyshin Formation) belongs to the upper Paleocene and is a stratigraphic equivalent of upper horizons of that sedimentary complex near the town of Kamyshin, which yields the so-called "Kamyshin flora." Thus, the formation history of Paleogene deposits in the Volga River lower reaches remains unclear, and stratigraphic scope and age of corresponding formations are ambiguously interpreted.

This article presents the results of study of organic-walled phytoplankton from the Paleocene deposits of Borehole 28 that was drilled by the Volgograd Geological Prospecting Expedition 30 km to the north of the town of Dubovka, near the Loza Farm (Fig. 2). The dinoflagellate assemblages recovered is used to date the Paleogene deposits more precisely and to establish stages of a sea basin development the lower Volga River basin.

SECTION DESCRIPTION

The Paleocene deposits in the depth interval of 27.0–171.0 m correspond to the Syzran', Kamyshin and Proleika formations, as they are defined by geologists of the Volgograd Geological Prospecting Expedition (rocks are described from the top downward, Fig. 3).

The Proleika Formation

27.0–29.0 m: gray fine-grained quartz–glauconite clay-free sandstone.

29.0–37.0 m: sand with gray and greenish gray quartz–glauconite sandstone interbeds and green glauconite laminae up to 5 mm thick.

37.0–43.0 m: greenish gray fine-grained sand alternating with sandstone and lean clay interbeds.

43.0–50.0 m: sand with laminae and nests of lean clays. The rock is of bright green color due to glauconite abundance.

50.0–52.0 m: gray sandstone that is greenish micaceous, polymictic, glauconite-bearing, and heterogranular at the top and platy at the base.

52.0–56.5 m: dark gray dense clay with numerous nests and interbeds of sand and silt.

56.5-62.0 m: greenish gray polymictic sandy silt that shows a complex texture owing to irregular occurrence of clay material. The lower part includes clay interbeds up to 0.1 m thick.

62.0–66.0 m: the basal horizon of the Proleika Formation that is composed of greenish gray fine-grained polymictic cross-bedded sandstone.

The Kamyshin Formation

66.0–86.0 m: greenish gray quartz sand with clay nests.

86.0–91.0 m: dark gray dense clayey silt with numerous interbeds and nests of sand (up to 2–3 cm thick).

91.0–96.0 m: complicatedly bedded siltstone with clay interbeds and gray sand laminae.

96.0–113.0 m: dark gray dense silty clay that alternates with sandy varieties, silt and gray to dark gray sandstone.

The Syzran' Formation

113.0–146.0: greenish gray to gray fine-grained polymictic silty sand with significant clay admixture. Sand is occasionally consolidated, intercalated with sandstone interbeds and yields abundant pelecypods and gastropods.

146.0–153.0 m: sandy opoka yielding large oyster shells in the upper part.

153.0–170.5 m: dark gray to black opoka, locally indistinctly bedded and enclosing sand and clay interbeds. The upper part is rich in sandy components, whereas clayey interbeds are concentrated in the lower one.

170.5–171.0 m: the basal horizon of the Syzran' Formation that is composed of gray medium-grained polymictic hard sandstones bearing pelecypod fragments.

Below there are Upper Cretaceous deposits.

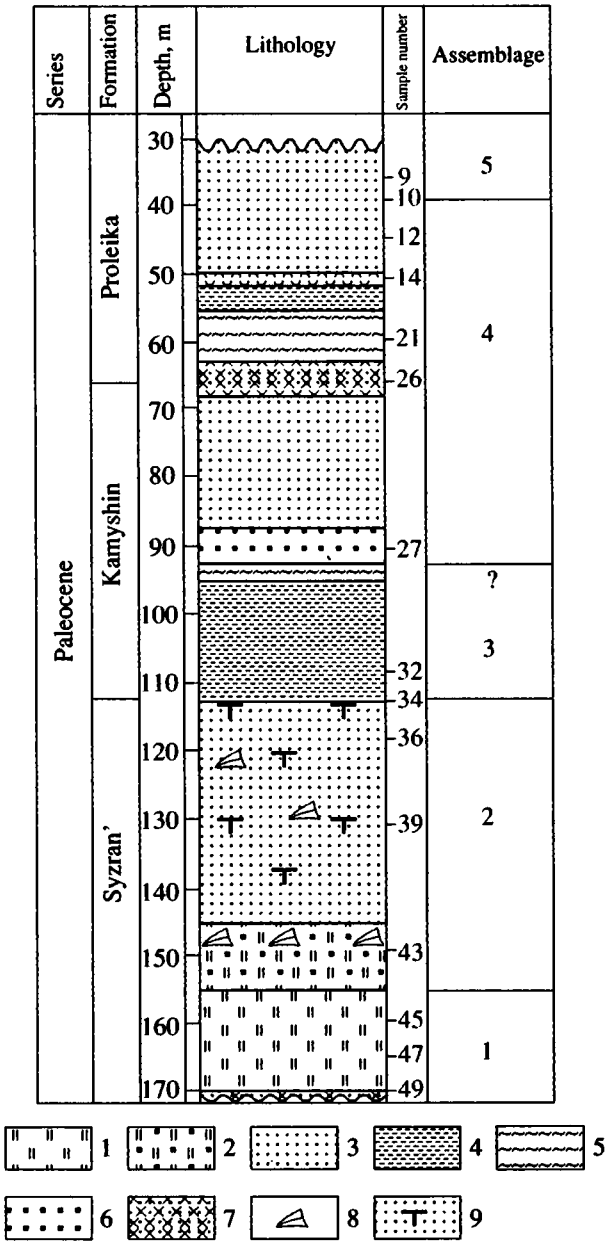

Fig. 3. Paleogene deposits recovered by Borehole 28 (formations in interpretation of geologists from the Volgograd Geological Prospecting Expedition): (1) opoka; (2) sandy opoka: (3) sand; (4) clay; (5) siltstone; (6) silt; (7) sandstone; (8) oyster banks, pelecypods, gastropods; and (9) slightly calcareous sand.

PALYNOLOGICAL CHARACTERISTICS

The entire section of marine deposits is characterized by microphytoplankton, spores, and pollen. Five palynological assemblages have been preliminary distinguished (table).

Assemblage 1. The assemblage is distinguished in the lower Syzran' Subformation (Samples 49, 47, 45; interval of 153.0–171.0 m). Organic-walled phytoplankton is represented by *Achomosphaera crassipellis, A. membraniforra, A. sagena, A. ramulifera, A. alcicornu, Achomosphaera* sp., *Alterbia recticornis, Alterbia* sp., *Alterbidinium* sp., *Areoligera senonensis, Areoligera* sp., *Batiacasphaera* sp., *Cerodinium* sp., *Cleistosphaeridium* cf. *aciculare, Cordosphaeridium inodes, C. gracilis, C. funiculatum, Cordosphaeridium* sp., *Cribroperidinium?* sp., *Deflandrea diebelii, Diodyx?* sp., *Diphyes colligerum, Eisenackia* sp., *Fibradinium anettoprense, Fibrocysta* sp., *Florentinia* cf. *ferox, Florentinia* sp., *Gonyaulax* sp., *Gonyaulacysta* sp., *Hafniasphaera fluens, H. septata, H. hyalospinosa, Hafniasohaera* sp., *Homotryblium* sp., *Hystrichokolpoma* sp., *Hystrichostrogylon coninckii, Hystri-*

Phytoplankton distribution throughout the section of Borehole 28

Genus \ Sample number	49	47	45	43	39	36	34	32	27	26	21	14	12	10	9
Trigonopyxidia sp.	10	8								3					
Phelodinium kozlowskii	64		4		4	1									
Palaeoperidinium sp.	17		4												
Dinogymnium sp.	6		1		2	1	1	2	8	2	2				
Spiniferites ramosus	28	9	19	3	30			20	8	24			15	37	55
Impagidinium? sp.	15				13						1			1	1
Fibradinium anettoprense	12	23	10		22	8									
Spiniferites sp.	140		4	3		18	13	17	20		30	5			7
Operculodinium sp.	26				9	6		9	3	3				4	
Microdinium sp.	20	5		1		5									2
Fibrocysta sp.	3														
Hystrichosphaeridium sp.	13	1	9	1		8				3		1		5	5
Odontochitina porifera	1							1							
Palaeocystodinium sp.	10	8	6												
Palaeocystod. bulliformum	2														
Oligosphaeridium sp.	41							6		1	6			4	
Hystrichokolpoma sp.	24	2	1						3		1	1			
Senoniasphaera inornata	25	14	38		1										
Senoniasphaera sp.			6												
Turbiosphaera? sp.	1														
Spiniferites cornutus	10	1													1
Operculod. centrocarpum	5	2			2	3		4					5	18	16
Cordosphaeridium inodes	4	1	16			11		2							
Cordosphaeridium sp.	17	3	4	5	16		1		2	2	7				1
Cribroperidinium? sp.	1														
Kallosphaeridium sp.	6	18	27		20	8	2			10		7	14	23	24
Lejeunecysta sp.	13													2	11
Homotryblium sp.	3				1										
Cordosphaeridium gracilis	5		10		10	8				7					
Alterbia sp.	3							6							6
Alterbidinium sp.	1			1	7	2									
Cordosphaeridum funiculatum	8		5												
Areoligera sp.	4				6					14					5
Thalassiphora pelagica	28	10	24	2	12	9				4					
Isabelidinium? sp.	2	2											17		
Gonyaulacysta sp.	12														
Achomoshaera sp.	32	11	9	4	4		9	18		22	13		5	6	15
Diphyes colligerum	5			2		1		1							
Prolixosphaer. xanthiopyxides	16														
Membranosph. maastrichtica	2	18	7	3	17	15									
Diodyx? sp.	2														
Systematophora sp.	5	3	4								17		4		
Deflandrea diebelii	3														
Paralecaniella indentata	10	6		1	7		4	23	33	1			6	17	16

Table. (Contd.)

Genus \ Sample number	49	47	45	43	39	36	34	32	27	26	21	14	12	10	9
Florentinia sp.	1														
Cleistosphaer. cf. *aciculare*	26	8		7											
Alterbia recticornis	2														
Lejeunia sp.	1														
Spiniferites r. granosus	5		25		13					9			4	18	15
Palaeocystodinium lidiae	10								1						
Florentinia cf. *ferox*		4													
Hystrichosphaer. tubiferum		5	4		27		2	14					4	6	11
Hafniasphaera fluens		10	4												12
Hafniasphaera septata		7	3		9	6				10		3	18	11	26
Hafniasphaera hyalospinosa			1												
Hafniasphaera sp.		2													6
Palaeotetradinium sp.		33	17												
Achomosphaera crassipellis		1					2	6		6			1	3	4
Kallosphaerid. brevibarbatum		79	6												
Dapsilidinium? sp.		4													
Areoligera senonensis		1	27		1	6		2		63		27	20	10	22
Eisenackia? sp.		3	1												
Batiacasphaera sp.		9					3	7						9	19
Gonyaulax sp.		1	3												
Tanyosphaeridium sp.		1						2							
Operculod. ?*machaerophorum*				5											
Prolixosphaeridium sp.				9											
Spinidinium ?*pilatum*				7	38	1									
Elytrocysta druggii				4						4					
Cleistosphaeridium sp.				7	6	5	8	6		16				6	16
Systematophora placacantha				4	9	3							1	4	1
Isabelidinium? *viborgense*				11	50										
Cerodinium speciosum				1			2	3							
Cordosphaerid. cf. *exilimurum*				4											
Fromea amphora				5											
Homotryblium abbreviatum				2		1	2	1							
Laciniadinium williamsii			1	1											
Spinidinium echinoideum					9	1		1							
Glaphyrocysta divaricata					8	1	2			75					
Microdinium ornatum					6	2									3
Laciniadinium sp.					24										
Palaeoperidinium pyrophorum					3	2		1							
Thalassiphora spinifera					3						1				
Cribroperid. cf. *tenuitabulatum*					5										
Palaeotetrad. minusculum					9					20			7	3	33
Alterbidinium circulum					12			6							
Achomosphaera alcicornu					1		1								1
Cerodinium striatum					4	1									

Table. (Contd.)

Genus \ Sample number	49	47	45	43	39	36	34	32	27	26	21	14	12	10	9
Cerodinium dartmooria					2					69	11		12	5	5
Pthanoperidinium sp.						6	1								
Cerodinium cf. *markovae*						4									
Circulodinium distinctum							4	14		6					3
Chatangiella sp.							3	6		2				2	
Phelodinium cf. *magnificum*							1								
Spinid. cf. *densispinatum*								1							
Glaphyrocysta ordinata								3					3		11
Insertae sedis									7		1		10	8	48
Cyclonephelium sp.			1						2	2					
Glaphyrocysta sp.										2			1	1	
Spiniferites r. membranaceus										9				3	
Areoligera coronata										29				1	2
Areoligera sentosa										3					
aff. Lentinia wetzelii		16	8								10				
Areoligera tauloma											8				
Achomosphaera sagena			1										4		
Alisocysta margarita													8		
Adnatosphaerid. ?vittatum													7	5	19
Desmocysta sp.													14		30
Conexímura cf. *fimbriata*														2	
Thalassiphora delicata														1	4
Apteodinium sp.														3	
Alisocysta sp. 2														14	43
Spiniferites r. multibrevis															4
Cerodinium sp.															2
Achomosphaera ramulifera			6												37
Hystrichostrog. ?membraniforum			2												5
Phytoplankton	700	329	318	83	422	143	61	182	87	421	108	44	180	232	547
Acritarchs	42	250	178	14	11		1	4	41	332	62	17	44	61	128
Spores and pollen	18	28		1	5	15	127	209	208	284	201	34	59	238	499

chosphaeridium tubiferum, Hystrichosphaeridium sp., *Impagidinium* sp., *Isabelidinium?* sp., *Kallosphaeridium brevibarbatum, Kallosphaeridium* sp., *Lentinia wetzelii, Lejeunecysta* sp., *Membranosphaera maastrichtica, Microdinium* sp., *Odontochitina porifera, Oligosphaeridium* sp., *Operculodinium centrocarpum, Operculodinium* sp., *Palaeocystodinium bulliformum, Palaeocystodinium* sp., *Palaeoperidinium* sp., *Palaeotetradinium* sp., *Paralecaniella indentata, Phelodinium kozlowskii, Prolixosphaeridium xanthiopyxid, Senoniasphaera inornata, Senoniasphaera* sp., *Spiniferites ramosus, S. ramosus granosus, S. cornutus, Spiniferites* sp., *Systematophora* sp., *Tanyosphaeridium* sp., *Thalassiphora pelagica, Trigonopyxidia* sp., and *Turbiosphaera?* sp. The spore–pollen assemblage includes single *Pinus* sp., *Trudopollis menneri, T.* sp., *Tricolpopollenites* sp., *Triporites* sp., and *Gleichenia* sp. Samples from the upper levels contain abundant acritarchs (up to 40% of all planktonic forms).

Assemblage 2. The assemblage characterizes the upper Syzran' Subformation (Samples 43, 39, 36; interval of 148.0–117.0 m). Phytoplankton consists here of *Achomosphaera alcicornu, Achomosphaera* sp., *Alterbidium circulum, Alterbidium* sp., *Areoligera senonensis, Areoligera* sp., *Cerodinium striatum, C. dartmooria, C.* cf. *markovae, Cleistosphaeridium* cf. *aciculare, Cleistosphaeridium* sp., *Cordosphaeridium inodes, C.*

gracilis, C. cf. *exilimurum, Cordosphaeridium* sp., *Cribroperidinium* cf. *tenuitabulatum, Dinogymnium* sp., *Diphyes colligerum, Elytrocysta druggi, Fibradinium anettoprense, Glaphyrocysta divaricata, Hafniasphaera septata, Homotryblium abbreviatum, Homotryblium* sp., *Hystrichosphaeridium tubiferum, Hystrichosphaeridium* sp., *Impagidinium?* sp., *Isabelidinium? viborgense, Kallosphaeridium* sp., *Laciniadinium williamsii, Laciniadinium* sp., *Membranosphaera maastrichtica, Microdinium ornatum, Microdinium* sp., *Operculodinium centrocarpum, Operculodinium* sp., *Palaeoperidinium pyrophorum, Palaeotertadinium minusculum, Paralecaniella indentata, Phelodinium kozlowskii, Pthanoperidinium* sp., *Senoniasphaera* sp., *Spinidinium densispinatum, Spinidinium echinoideum, Spinidinium* cf. *pilatum, Spiniferites ramosus, S. ramosus granosus, Spiniferites* sp., *Systematophora placacantha, Thalassiphora pelagica*, and *T. spinifera.* The spore-pollen assemblage is analogous to the preceding one. Scarce acritarchs were found.

Assemblage 3. The assemblage characterizes the lower part of the Kamyshin Formation (Samples 34 and 32; interval of 111.0–105.0 m). The dinocyst assemblage includes *Achomosphaera crassipellis, A. alcicornu, Achomosphaera* sp., *Alterbia* sp., *Alterbidinium circulum, Areoligera senonensis, Batiacasphaera* sp., *Cerodinium speciosum, Chatangiella* sp., *Circulodinium distinctum, Cleistosphaeridium* sp., *Cordosphaeridium inodes, Cordosphaeridium* sp., *Dinogymnium* sp., *Diphyes colligerum, Glaphyrocysta divaricata, G. ordinata, Homotryblium abbreviatum, Hystrichosphaeridium tubiferum, Kallosphaeridium* sp., *Spiniferites ramosus, Spiniferites* sp., *Odontochitina* sp., *Oligosphaeridium* sp., *Operculodinium centrocarpum, Operculodinium* sp., *Palaeoperidinium pyrophorum, Paralecaniella indentata, Phelodinium* cf. *magnificum, Pthanoperidinium* sp., *Tanyosphaeridium* sp., *Spinidinium* cf. *densispinatum, Spinidinium echinoideum.* Acritarchs are absent.

The spore–pollen assemblage shows equal amounts of pollen of gymnosperms (*Pinus* sp., *Podocarpus* sp., Taxodiaceae-Cupressaceae sp., *Glyptostrobus* sp.) and that of the "stemmas" Normapolles Pflug and Postnormapoles Pflug. The "stemma" Normapolles is represented by *Trudopollis hemiperfectus, T.* sp., *Extraporopollenites* sp., *Sporopollis* sp. and the "stemma" of Postnormapolles, by *Tricolporopollenites* sp., *Triporopollenites* sp. There occur single pollen grains of *Myrica* sp., Hamamelidaceae? sp., and *Quercus* sp. (according to the natural classification).

Assemblage 4. The assemblage is distinguished in the upper part of the Kamyshin Formation and in the lower part of the Proleika Formation (Samples 27, 26, 21, 14, and 12; interval of 87.0–45.0 m). Phytoplankton of low diversity and abundance is represented by *Areoligera* spp. + *Claphyrocysta* spp. and *Cerodinium dartmooria.* The other part of the spectrum consists of *Achomosphaera crassipellis, A. sagena, Achomosphaera* sp., *Adnatosphaeridium* cf. *vittatum, Alisocysta margarita, Chatangiella* sp., *Circulodinium distinctum, Cleistosphaeridium* sp., *Cordosphaeridium gracilis, Cordosphaeridium* sp., *Cyclonephelium* sp., *Desmocysta* sp., *Dinogymnium* sp., *Elytrocysta druggii, Hafniasphaera septata, Hystrochokolpoma* sp., *Hystrichosphaeridium tubiferum, Hystrichosphaeridium* sp., *Impagidinium?* sp., *Isabelidinium?* sp., *Kallosphaeridium* sp., *Lentinia wetzelii, Oligosphaeridium* sp., *Operculodinium centrocarpum, Operculodinium* sp., *Palaeocystodinium lidiae, Palaeotetradinium minusculum, Paralecaniella indentata, Spiniferites ramosus, S. ramosus granosus, S. ramosus membranaceus, Spiniferites* sp., *Systematophora placacantha, Systematophora* sp., *Thalassiphora pelagica*, and *T. spinifera.* Acritarchs constitute to 8–15% in average but reach 30% in Sample 26.

The spore–pollen spectrum of Assemblage 4 is similar to that of Assemblage 3. It also contains different *Trudopollis* species (*T. hemiperfectus, T. pompeckii, T. ordinatus*, and *T.rugosus*), as well as *Tricolporopollenites* sp. and *Triporopollenites* sp. The "stemma" Postnormapolles Pflug is of a more diverse composition because of addition of *Triatriopollenites* cf. *pseudorurensis* and *Subtriporopollenites* cf. *anulatus.* Among pollen genera of natural classification, there are newly appeared *Acer?* sp., *Salix* sp., and *Carya* sp. Identified spore taxa are *Stereisporites crasus, Lycopodium* sp., *Densiosporites* sp., *Selaginella* sp., single *Sphagnum* sp., *Anemia* sp., and *Gleichenia* sp. Abundance of spores and pollen is comparable with that of phytoplankton.

Assemblage 5. The assemblage characterizes the upper part of the Proleika Formation (Samples 9, 10; interval of 38.0–39.0 m). It consists of *Achomosphaera crassipelis, A. alcicornu, A. ramulifera, Achomosphaera* sp., *Adnatosphaeridium* cf. *vittatum, Alisocysta* sp. 2, *Alterbia* sp., *Apteodinium* sp., *Areoligera senonensis, A. coronata, A.* sp., *Batiacasphaera* sp., *Cerodinium dartmooria, Cerodinium* sp., *Chatangiella* sp., *Circulodinium distinctum, Cleistosphaeridium* sp., *Conneximura* cf. *fimbriata, Cordosphaeridium* sp., *Desmocysta* sp., *Glaphyrocysta ordinata, Glaphyrocysta* sp., *Hafniasphaera fluens, H. septata, Hafniasphaera* sp., *Hystrichosphaeridium tubiferum, Hystrichosphaeridium* sp., *Hystrichostrogylon membraniforum, Impagidinium?* sp., *Kallosphaeridium* sp., *Lejeuncysta* sp., *Microdinium ornatum, M.* sp., *Oligosphaeridium* sp., *Operculodinium centrocarpum, O.* sp., *Palaeotetradinium minusculum, Paralecaniella indentata, Spiniferites ramosus, S. ramosus granosus, S. ramosus membranaceus, S. ramosus multibrevis, S. cornutus, S.* sp., *Systematophora placacantha*, and *Thalassiphora delicata.*

The spore–pollen assemblage is sharply different from the preceding one. It is devoid of pollen of the "stemma" Normapolles Pflug, whereas representatives of "stemma" Postnormapolles Pflug are dominant,

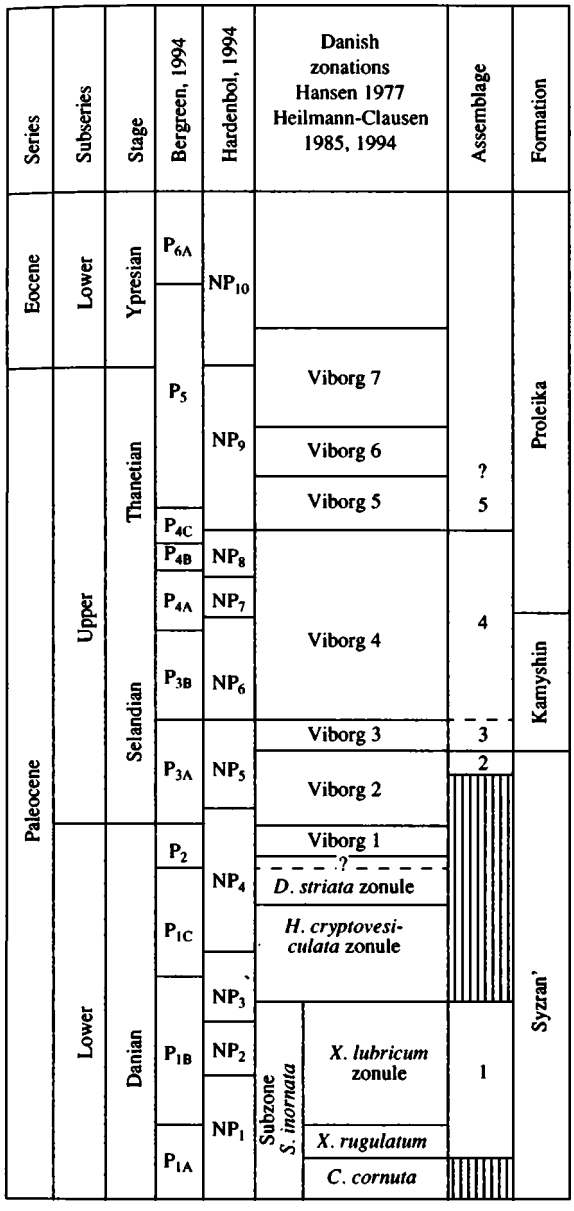

Fig. 4. Correlation scheme for the distinguished assemblages.

exemplified by the formal genus *Tricolporopollenites* sp. and by gymnosperms *Pinus* sp., *Ginkgo* sp., *Taxodiaceae-Cupressaceae* sp., and *Glyptostrobus* sp. The last studied sample yielded abundant pollen of Myrtaceae.

DISCUSSION

The phytoplankton assemblages from Borehole 28 are correlative with zonal assemblages distinguished by Hansen (1977) and Heilmann-Clausen (1985, 1988) in the Paleocene deposits of Denmark (Fig. 4).

Phytoplankton of Assemblage 1 from the lower Syzran' Subformation includes many forms in common with the assemblage of the *Senoniasphaera inornata* Subzone (Hansen, 1977). These are *Senoniasphaera inornata, Hafniasphaera* spp., *Spiniferites* spp., *Fibradinium anettoprense, Cordosphaerinium inodes*, and *Achomosphaera alcicornu.* In the stratotype, the *Senoniasphaera inornata* Subzone characterizes the lower–middle Danian, i.e., the interval of NP1–NP3 (lower part) zones. Considering the last occurrence level of *Senoniasphaera inornata*, Heilmann-Clausen (1994) indicated a high correlative value of this taxon in the Danian deposits. The basal *Carpatella cornuta* Beds of the *S. inornata* Subzone (Hansen, 1977), which have been recently recognized as an independent zone (Andreeva-Grigorovich, 1991) corresponding to the lower part of Zone NP1, are missing from the section under consideration. Accordingly, stratigraphic range of the Assemblage 1 may be compared with the dinocyst zone D1 (Costa and Manum, 1988), nannoplankton zones NP1 (middle part)–NP3 (lower part) in interpretation of Martini (1971), and with zones P1A–P1B of planktonic foraminifers (Blow, 1969; Berggren, 1972).

In the lower Syzran' Subformation, Glezer (1995) recognized the diatom *Hemiaulus rossicus* Zone of the lower Danian. In the same deposits, Kozlova (1984) established the radiolarian *Buryella alifera* Zone also corresponding to the lower Danian. New data on dinocyst distribution thus confirm that the lower Syzran' Subformation is of the Danian age, as is suggested by Glezer and Kozlova.

The abundance of acritarchs in the upper part of the Syzran' Formation points to the basin shoaling followed by the break in marine sedimentation during the late Danian–early Selandian.

Assemblage 2 is distinguished at the appearance level of *Isabelidinium? viborgense* that marks a distinct reference level in the Paleogene sequence of the Danish basin (Heilmann-Clausen, 1985, 1994). The first and last occurrence levels of this species are inside the Viborg 2 and at the base of the Viborg 3 zones, respectively. Assemblage 2 is similar in composition to the assemblage of the Viborg 2 Zone, as it includes *Palaeoperidinium pyrophorum, Cerodinium speciosum*, and *Cerodinium striatum* characteristic of the latter. Deposits characterized by Assemblage 2 are correlative with the *Cerodinium speciosum* Zone (Powell, 1992) and, partially, with Zone D3 (Costa and Manum, 1988) and Zone NP5 (Martini, 1971). The assemblage is analogous to the mid-Selandian assemblage from the type sections of Denmark. Thus, in the section under consideration, there is a hiatus between the lower and upper Syzran' subformations. The hiatus range corresponds to the upper Danian–lower Selandian.

Data on nannoplankton (Musatov, 1993) also indicate the early Selandian age (NP5) of the upper Syzran' Subformation. The molluscan assemblage from this

subformation (Zubkovich, 1960) is similar to that from the upper Paleocene marls of the Crimea and to the Thanetian assemblage of Western Europe.

Assemblage 3 characterizes the last occurrence of *Palaeoperidinium pyrophorum* and *Cerodinium striatum*. Heilmann-Clausen (1985, 1994) distinguished disappearance of these species at the top of the Viborg 3 Zone. Unlike the Danish assemblage, Assemblage 3 does not demonstrate the maximum abundance of *Palaeoperidinium pyrophorum* characteristic of the upper part of the Viborg 3 Zone. This may be however explained by the lack of data for the unstudied section interval between samples 27 and 32. For this reason, the boundary between assemblages 3 and 4 is provisionally placed at the level of lithological changes. Provided these reservations, the interval of Assemblage 3 can be correlated to the mid-Selandian Viborg 3 Zone (Heilmann-Clausen, 1985, 1994) and to interval of zones NP5 (upper part)–NP6 (base). Other correlative units are the *Palaeoperidinium pyrophorum* Zone (Powell, 1992) and, partially, the Zone D4 (Costa and Manum, 1988). Assemblages 2 and 3 are also similar in composition to the *Cerodinium speciosum* assemblage distinguished in the Paleogene Talitsy and Serov (lower part) formations of the southern trans-Urals region (Vasil'eva, 1990).

Assemblage 4 of a lowly diverse composition is dominated by *Areoligera* spp., *Glaphyrocysta* spp., and *Cerodinium dartmooria*. In composition and ranges of phytoplankton species, Assemblage 4 is analogous to that characteristic of the Viborg 4 Zone (Heilmann-Clausen, 1985). However, *Alisocysta margarita* occurring throughout the Viborg 4 Zone (Heilmann-Clausen, 1985, 1994) was found only in the uppermost of samples that yield the Assemblage 4. Absence of this species below may be attributed to the lithological peculiarities of the section. The Viborg 4 Zone of the Danish basin is correlated with the interval of zones NP6–NP8. Assemblage 4 is therefore of late Selandian–early Thanetian age and correlative, in addition, with the dinocyst assemblage from the "Heersian Stage" and the Gelinden Marl of Belgium (Schumacher-Lambry, 1978). The above age is also inferable from similarity between the Kamyshin flora and the Gelinden type flora of the Paleocene. The palynological composition of assemblages 3 and 4 is analogous to that of the integral late Paleocene spore–pollen spectrum characterizing the Kamyshin Formation and Proleika beds in the Volga River region (Kuznetsova, 1973).

Assemblage 5 characterizes the first occurrence level of dinocysts *Alisocysta* sp. 2 (Heilmann-Clausen, 1985). According to Heilmann-Clausen (1985), *Alisocysta* sp. 2 is a member of the *Alisocysta margarita* phylogenetic succession and occurs in the Thanetian deposits of Denmark, where these forms appear at the base of the Viborg 5 Zone. Powell (1992) distinguished their first occurrence in the *Apectodinium hyperacanthum* Zone of Western Europe. He correlated this unit with the Viborg 5 Zone and, partially, with the Zone NP9 (Martini, 1971). Thus, *Alisocysta* sp. 2 is a reliable stratigraphic marker first appearing in the Thanetian. As for dinocysts proper, the interval of Assemblage 5 appears to be to a part of the Viborg 5 Zone (Heilmann-Clausen, 1985) and an equivalent of the *Apectodinium hyperacanthum* Zone (Powell, 1992) and Zone D4 (Costa and Manum, 1988). The spore–pollen assemblage from this level differs from the preceding one because of predominance of pollen characterizing "stemma" Postnormapolles Pflug. According to all data mentioned above, the beds with Assemblage 5 can be referred to the Thanetian.

CONCLUSION

Analysis of Paleogene marine deposits penetrated by Borehole 28 revealed their palynological characteristics enabling correlation of the distinguished phytoplankton assemblages. Three periods in development of the corresponding sea basin corresponded to the early Danian (the lower Syzran' Subformation), Selandian (the upper Syzran' Subformation and the lower part of the Kamyshin Formation) and the Thanetian (the upper part of the Kamyshin and Proleika formations). As is found out, the late Danian–earliest Selandian interval marks a break in sedimentation. Accordingly, it is inexpedient to apply the term "Syzran' Formation" for the entire lower sequence of opoka–sandy deposits divided by such a significant hiatus.

Data on microphytoplankton distribution show that the lower Paleogene deposits in the Volga River region are well correlative with dinocyst zones known in Denmark and Belgium. This suggests close connections between corresponding paleobasins during the Paleocene time. Available data on siliceous microplankton groups (Glezer, 1995; Kozlova, 1984) support the age determinations based on dinocysts.

The results obtained are important for developing the Paleogene stratigraphy of the Volga River region. In the stratigraphic scheme available at present, sedimentary formations of the region are dated controversially, and new results should be taken into consideration in the final version of the scheme.

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Palynological Assemblages from the Middle Eocene Kuma Horizon and Its Age Analogues in Adjacent Regions

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Abstract—The paper discusses the composition of organic-walled phytoplankton, spores, and pollen from the middle Eocene Kuma Horizon and its age analogues in adjacent parts of the East European platform, Scythian, and Turan plates. Anomalous contents of several taxons are established in the sediments that formed in anoxic environments. As compared with the organic-walled phytoplankton assemblages from the Kuma Horizon, those from the fine-grained clayey sediments of the upper Eocene Belaya Glina Horizon that accumulated in the open well-aerated sea basin with the normal salinity are characterized by the higher diversity and greater dispersion degree. Contrary to the Kuma palynological assemblages, the abundance of pollen and spores in the latter is below 5% of palynomorphs deposited in the shelf zone of the sea basin. Sediments of the Kuma Formation that were deposited in reducing environments are characterized by the extremely high content of amorphous organic matter (up to 95–98%) represented by detritus of the algal, ichthyiological, and partly cyanobacterial origin. The Kuma Horizon corresponds to two dinocyst subdivisions: the lower *Areosphaeridium diktyoplokus–Dracodinium condylos* and upper *Rhombodinium perforatum–Rhombodinium porosum* zones.

Key words: dinocysts, prasinophytes, acritarchs, spores, pollen, Kuma Formation, horizon, organic-walled phytoplankton, Eocene, North Caucasus.

INTRODUCTION

Vassoevich (*Trudy...*, 1934) was first to unite the sequence of laminated bituminous marls, which are usually several dozens of meters thick in the Caucasus, into the Kuma Formation. This sequence with stratotype area in the Kuma River basin is developed within the entire Greater Caucasus homocline and traceable further southward in Georgia and westward in the Crimea. The sequence retains everywhere its compositional properties and is easily recognizable between the Keresta and Belaya Glina white-colored clayey–calcareous formations.

The middle Eocene (Bartonian) age of the Kuma Formation is substantiated by finds of calcareous microplankton (planktonic foraminifers of the *Truncorotaloides rohri* = *Globigerina turcmenica* Zone; Krasheninnikov, 1974; Bugrova, 1988) and nannoplankton of the upper part of the *Discoaster saipanensis* and lower part of the *Chiasmolithus oamaruensis* zones (Martini and Müller, 1986; Muzylev, 1998). Based on the palynological assemblage, Panova (*Prakticheskaya palinostratigrafiya*, 1990) referred the Kuma sequence to the *Castanopsis pseudocingulum–Rhus regularis* Zone. Thus, in opinion of the mentioned authors, the Kuma Formation and corresponding horizon are most likely of the middle–late Bartonian age.

A high content of sufficiently fresh organic matter in the Kuma marls was noted long ago. The sediments are characterized by the extremely high concentration of dispersed amorphous substance of the plant origin, fish detritus, organic-walled phytoplankton, spores and pollen. Sometimes, the content of fish remains belonging to species *Lyrolepis caucasica* is so high that the enclosing sediments have been termed the *Lyrolepis* Beds. The high bitumen and sulfide contents in the Kuma Formation allowed the researchers to conclude that it was most likely deposited in H_2S-contaminated environments. This favored preservation of abundant and sufficiently fresh organic matter in sediments. The occurrence of remains of deep-sea species amid the ichthyofauna suggests the maximum depth of the basin to be up to 1000 m and more (Danil'chenko, 1960).

North of the Caucasus, the composition of constituting rocks of the Kuma Horizon changes. Toward the axial part of the Dnieper–Donets depression, marls become lighter and show a lower bitumen content, although the content of organic matter, particularly of the plant origin, remains significant in them. These sediments were deposited in oxidizing environments.

In the Kiev Formation, the lower part of which in the platform areas of Ukraine is mainly composed of marls, the Kuma Formation corresponds only to its upper beds of carbonate-free clays or, in marginal areas of the sea basin and on rises, to siltstones and siliceous–terrigenous strata. In intermediate facies of the Rostov salient, the age analogues of the Kuma Formation are composed of alternating sandstones, siltstones, and clays. In the Crimea, the formation corresponds to the sequence

of porous brown marls crowning the Bodrak regional stage. Like in the Caucasus, these marls were deposited under conditions of the hampered oxygen exchange. In the Voronezh anteclise, where the content of carbonate in rocks is lower, the Kuma Formation can correspond, as it was assumed by Semenov (1965), to the Tishki Formation of the Severskii Donets River basin.

In the zone between the Ciscaucasia and Lower Volga region, the Kuma Formation retains generally its composition. In the Severnye Ergeni area, it can be distinguished in its complete range, although Panteleev (1947) referred the marly sequence of this area to the lower Solonka Subformation. In the Mangyshlak area, calcareous clays with *Lyrolepis caucasica* that are easily correlative with the Kuma Formation are united into the Sharym Formation. Further to the east, toward the central part of the Turan plate, age analogues of the Kuma Formation become less rich in carbonate and are replaced in the Northern Ustyurt and Aral regions by silty–sandy sediments of the upper part of the Saksaul'skaya Formation. The diachronous type of the boundary between the Saksaul'skaya and overlying Chegan formations hampers correlation of marine middle Eocene sequences of Kazakhstan and the Crimea–Caucasus region.

The performed study of organic-walled phytoplankton and palynomorphs of vascular plants pursued the following goals: (1) to define their assemblages in sediments that were deposited in anoxic environments and to compare them with those from the well-aerated shallow-water settings; (2) to reconstruct the phytoplankton composition in the coastal zone; (3) to define position of the Kuma Horizon in the regional Paleogene dinocyst scale; and (4) to clarify the probable influence of the climatic zoning on composition of organic-walled phytoplankton assemblages of the late middle Eocene. The data cited in this article were partly published elsewhere (Akhmet'ev and Zaporozhets, 1992; Zaporozhets, 1998, 1999).

Samples collected from some reference sections of the North Caucasus, East European platform, Scythian and Turan plates (Rostov salient, Severnye Ergeni, Voronezh anteclise, Northern Ustyurt) by myself and other geologists served as a material for this study (Fig. 1).

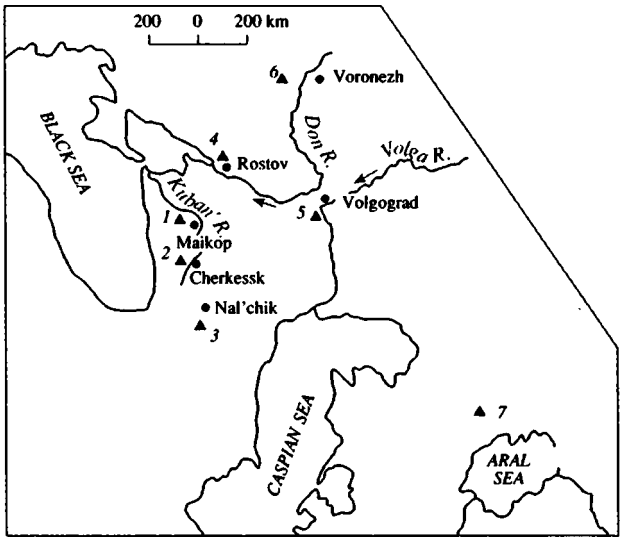


Fig. 1. Location of the studied sections: (*1*) Belaya River; (*2*) Kuban' River; (*3*) Kheu River; (*4*) Borehole 571 (Bessergenevskaya area, Rostov salient); (*5*) Borehole 45A (Derbity Settlement, Severnye Ergeni); (*6*) Boreholes 7250 and 7252 (Novyi Oskol, Voronezh anteclise); and (*7*) Mt. Sandal (Northern Ustyurt).

PALYNOLOGICAL CHARACTERISTIC OF SECTIONS

Northern Homocline of the Greater Caucasus

In the North Caucasian sections, the Kuma Formation was studied in bank exposures along the Belaya, Kuban', and Kheu rivers where it is 32, 45, and 50–60 m thick, respectively (Fig. 2). In all three sections, the formation is composed of platty porous marls with concretions and interbeds of sulfides usually decomposed in the oxidation zone, and with abundant fish remains and amorphous algal detritus visible to the unaided eye. The Kuma Formation is separated from the underlying Keresta and overlying Belaya Glina formations by transitional layers from several to 5–7 m thick. These layers are represented by alternating light brown Kuma marls and white, more calcareous or, to the contrary, more clayey rock varieties characteristic of the Keresta and Belaya Glina formations. This lithological "recurrence" is accompanied by a biotic recurrence, i.e., by the repeated occurrence of the same organic-walled phytoplankton and other microfossils (e.g., benthic foraminifers and others) in the transitional layers. These distribution patterns also established in previous paleontological studies emphasize the ecological dependence of distribution of the assemblages. The bedded structure of monotonous marly rocks in some intervals of the section can be observed within the Kuma Formation, as it is best seen in sections along the Belaya and Kuban' rivers. A more uniform structure is characteristic of the Kuma Formation exposed along the Kheu River, where its lower part only encloses interbeds of dark-colored bentonite clays formed after the ash layers. Altered ash layers are also present in the section along the Belaya River, where they occupy approximately the same stratigraphic level.

The study of over 20 samples from all three North Caucasian sections of the Kuma Formation allowed me to define some general regularities in distribution of organic matter and palynomorphs. In darkest rock varieties, 85–95% or, less commonly, 99% of the macerate are represented by amorphous substance of the algal and, probably, cyanobacterial origin, and by fine-grained fish detritus. Organic matter formerly dispersed

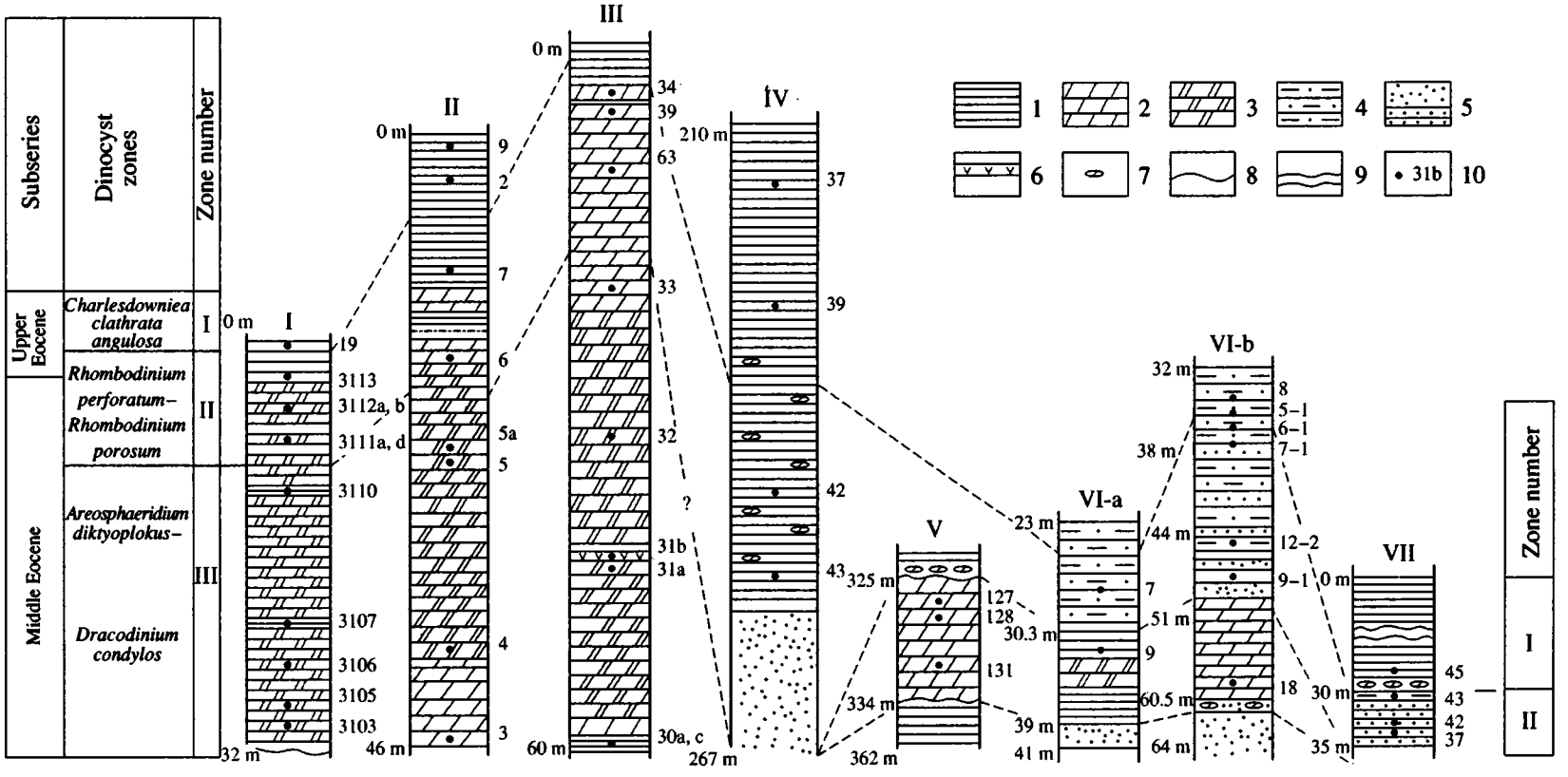
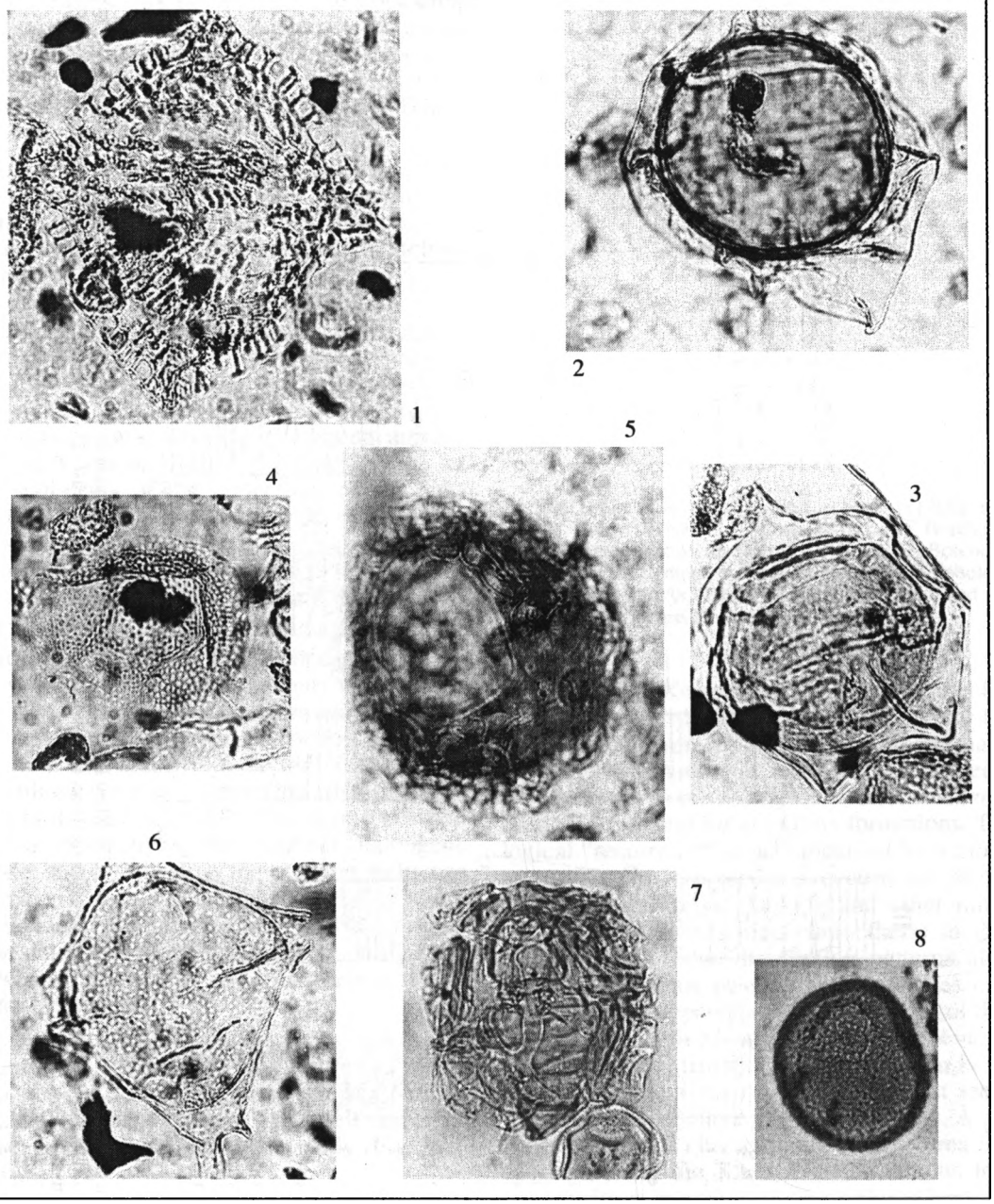


Fig. 2. Correlation of studied sections: (I) Belaya River; (II) Kuban' River; (III) Kheu River; (IV) Borehole 571; (V) Borehole 45A; (VI-a) Borehole 7250: (VI-b) Borehole 7252; (VII) Mt. Sandal. Lithology: (1) clay, (2) marlaceous clay, (3) marl, (4) silt, siltstone, (5) sand, sandstone, (6) volcanic ash, (7) phosphorite concretions; (8) hiatus; (9) gap in the column; (10) sample locality and number.

Plate I



Organic-walled phytoplankton of the Kuma Formation and its age analogues (Plates I–II)

Plate I: (1) *Charlesdowniea coleothrypta* subsp. *rotundata* (Chateaneuf and Gruass-Cavagnetto) Lentin and Vozzhennikova, northern Ustyurt Plateau, Mt. Sandal, Saksaul'skaya Formation, Sample 42ch/d; (2) *Deflandrea phosphoritica* Eisenack, Severnye Ergeni, Kuma Formation, Borehole 45A, Sample 131; (3) *Deflandrea phosphoritica* subsp. *phosphoritica* Eisenack, northern Ustyurt Plateau, Saksaul'skaya Formation, Sample 42ch/d; (4) *Heteraulacacysta porosa* Bujak, the same locality; (5) *Samlandia chlamydophora* Eisenack, Severnye Ergeni, Kuma Formation, Borehole 45A, Sample 133; (6) *Rhombodinium porosum* Bujak, northern Ustyurt Plateau, Saksaul'skaya Formation, Sample 42ch/d; (7) *Alisocysta* sp., North Caucasus, Kuban' River, Kuma Formation, Sample 5A; (8) *Tectatodinium* sp., the same locality. Magnification is ×600 in figs. 2, 5, 7, and 8, and ×500 others.

Plate II

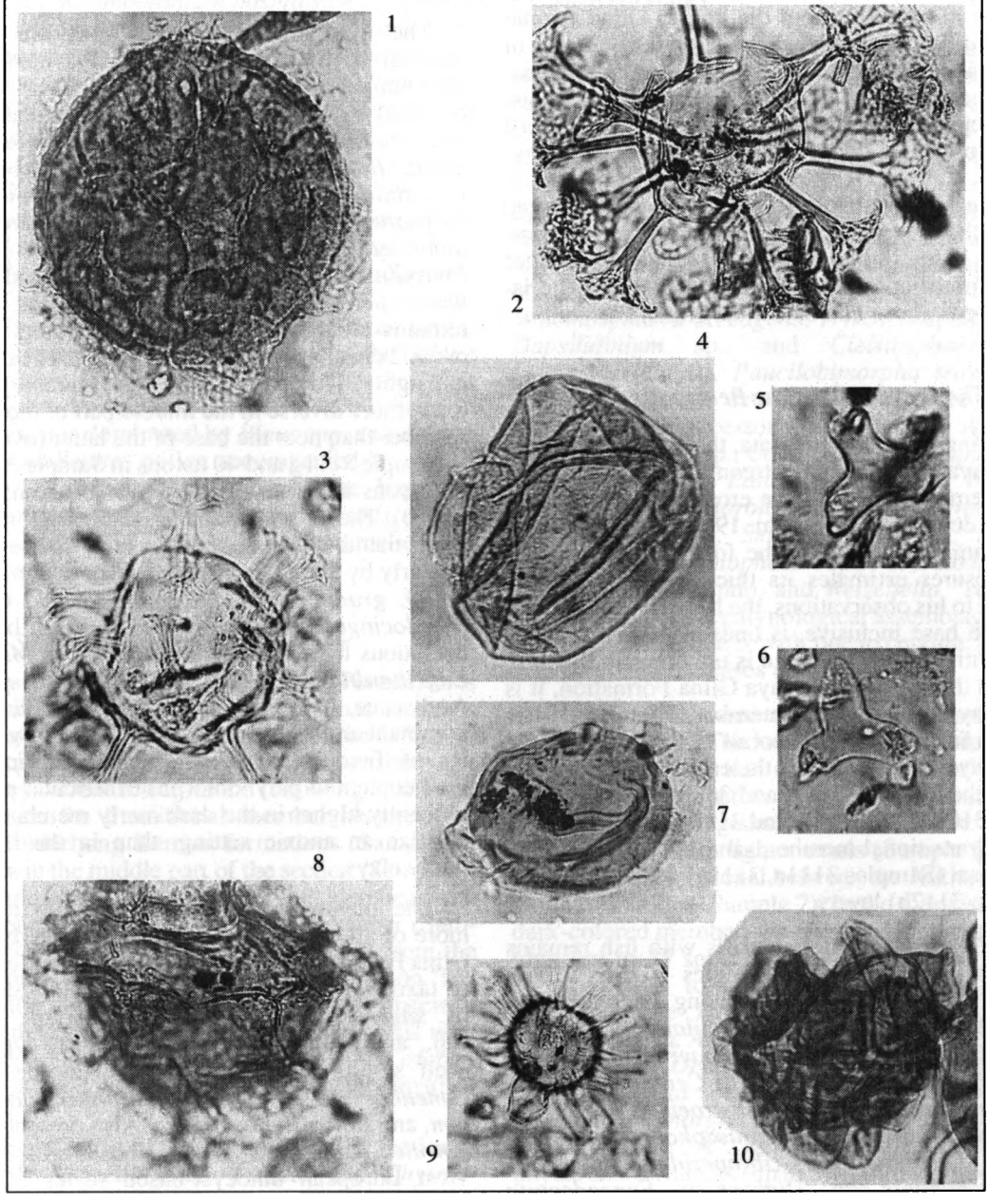


Plate II: (1) *Damassadinium* (*Danea*) *crassimuratum* (Wilson) Fensome *et al.*, North Caucasus, Kuban' River, Kuma Formation, Sample 5A; (2) *Areosphaeridium diktyoplokus* (Klumpp) Eaton, northern Ustyurt Plateau, Saksaul'skaya Formation, Sample 42ch/d; (3) *Homotryblium plectilum* Drugg et Loeblich, Severnye Ergeni, Kuma Formation, Borehole 45A, Sample 131; (4) *Chytroeisphaeridia* sp., North Caucasus, Kuban' River, Kuma Formation, Sample 5A; (5) *Paucilobimorpha triradiata* de Coninck, Severnye Ergeni, Kuma Formation, Borehole 45A, Sample 131; (6) *Paucilobimorpha granuligera* de Coninck, the same locality; (7) *Ptanospermella* sp., North Caucasus, Kuban' River, Kuma Formation, Sample 8/85; (8) *Wilsonidium* sp., Severnye Ergeni, Kuma Formation, Borehole 45A, Sample 131; (9) *Diphyes colligerum* (Deflandre and Cookson) Goodman and Winter, the same locality; and (10) *Hystrichokolpoma bullatum* Wilson, North Caucasus, Kuban' River, Kuma Formation, Sample 9^{k}/85. Magnification is ×600 for all figs.

in the uniform manner form accumulations in the upper layers of the Kuma Formation and disappears almost completely in basal layers of the Belaya Glina Formation. In addition to dispersed organic matter, rocks of the formation yield also pollen and spores approximately in equal proportions, fragments of cuticular tissues, dinocysts, acritarchs, and prasinophytes. The last group forms up to 50% of the organic-walled phytoplankton. It is noted that darker rock varieties, particularly those of the transitional layers, are characterized by the much higher content of higher plant palynomorphs. In the light-colored rocks, abundance of the latter sharply diminishes to the background level characteristic of the beds above and below the Kuma Formation.

The Section along the Belaya River

According to the drilling data, the Kuma Formation in the Belaya River basin upstream of the Abadzekhskaya Settlement rests with the erosional surface upon Paleocene deposits (Grossgeim, 1960). Yu.O. Gavrilov (pers. comm.) who studied the formation directly in bank exposures estimates its thickness to be 32 m. According to his observations, the lower part of the formation, the base inclusive, is unexposed and its relationship with underlying strata is unknown in this section. From the overlying Belaya Glina Formation, it is separated by the transitional member (4.5 m). Samples were taken from different intervals of the section: from the basal layer directly above the erosional surface and also from the levels of 3, 11, and 24 m above the latter (Samples 3103, 3105, 3107, and 3110, respectively). In the upper transitional member, samples were collected from its basal (Samples 3111a, 3111g) and upper (Samples 3112a, 3112b) layers.

Monotonous dark-colored marls with fish remains and marcasite concretions (Samples 3110b, 3105b, 3107b, 3110b) contain the following phytoplankton forms: *Areosphaeridium diktyoplokus, A.* sp., *Adnatosphaeridium* sp., *Achomosphaera* sp., *Achilleodinium* sp., *Caligodinium.* sp., *Cerebrocysta* sp., *Cerodinium diebelii, C.* sp., *Chytroeisphaeridia* sp., *Cleistosphaeridium* sp., *Cordosphaeridium* spp. (including *C. exilimurum*), *Cribroperidinium tenuitabulatum, Deflandrea* spp., *Diphyes* sp., *Enneadocysta arcuata, Horologinella* sp., *Hystrichosphaeropsis* sp., *Impagidinium* sp., *Impletosphaeridium* sp., *Lejeunecysta globosa, Manumiella* sp., *Microdinium* sp., *Operculodinium* sp., *Pentadinium* sp., *Phthanoperidinium* sp., *Rottnestia borussica, Selenopemphix nephroides, Spiniferites* spp., *Tectatodinium* sp., *Wetzeliella "echinulata."* Prasinophytes and acritarchs are represented by *Paucilobimorpha granuligera, Crassosphaera* sp., *Cymatiosphaera* sp, large *Leiosphaeridia* sp., and *Ptanospermella* sp. In every sample, about 20% of cyst fragments remained undetermined. *Pinus* spp., *Betula* sp., *Castanopsis pseudocingulum, Myrica* sp., *Ilex* sp., *Rhus* sp., *Nyssa* sp., as well as abundant pollen of form taxons were recognized amid spores and pollen.

The dinocyst assemblage from the transitional member is the same in general. Prevalent are *Enneadocysta* and *Microdinium* forms. *A. diktyoplokus* is replaced by *E. arcuata.* Amid newly appeared forms, there are *Rhombodinium draco, Dracodinium rhomboideum, Batiacasphaera sphaerica, Cyclopsiella* sp., *Dapsilidinium* sp., *Heteraulacacysta* spp. (*H. leptalea, H. pustulata*) *Melitasphaeridium asterium, Microdinium reticulatum, Palaeocystodinium golzowense, Pterodinium* sp., *Systematophora* sp., and *Thalassiophora pelagica.* Composition of green algae also remains almost unchanged. In two pairs of samples taken 2 cm apart from dark-colored (3111a and 3112b) and light (3111g and 3112a) rock varieties, phytoplankton is more diverse in the middle part of the transitional member than near the base of the latter (over 30 taxons in Sample 3111g and 40 taxons in Sample 3112a versus 11 taxons in Sample 3111a and 15 taxons in Sample 3112b). The palynological assemblage from the transitional member is dominated by angiosperm pollen, particularly by that of evergreen Fagaceae (*Quercus gracilis, Q. gracilliformis, Q. coniferta,* and *Castanopsis pseudocingulum*). Diverse are evergreen broad-leaved deciduous thermophilic forms, such as *Magnolia* sp., *Engelhardtia* sp., *Rhus* sp., *Platycarya* sp., *Ilex* sp., Araliaceae, *Nyssa* sp., and others. The *Pinus* pollen is dominant amid conifers. Present as single grains is pollen of Taxodiaceae, *Podocarpus,* and *Ephedra.* The total content of palynomorphs of vascular plants is significantly higher in the dark marly members that characterize an anoxic setting, than in the light-colored marly clays.

The phytoplankton assemblage (up to 90% and more of all palynomorphs) from the overlying Belaya Glina Formation is more diverse, represented by dozens of taxons. Prevalent are species *Achomosphaera* spp. (*A. sagena* included), *Impagidinium* sp., *Spiniferites* spp., and *Systematophora* sp. that are typical of the shelf setting. Characteristic late Eocene taxons are *Enneadocysta arcuata, Cordosphaeridium funiculatum,* and *Rottnestia borussica.* Also present is *Charlesdowniea clathrata angulosa,* the zonal species of the West European dinocyst-based scales of the upper Eocene. *Achilleodinium* sp., *Cannosphaeropsis* sp., *Corrudinium* sp., *Dinopterygium* sp., *Fibrocysta* sp., *Lophocysta* sp., *Microdinium* sp., *Pterodinium* sp., *Turbiosphaera* sp., and *Wilsonidium* sp. occur as single specimens.

In Sample 3113 taken directly at the base of the Belaya Glina Formation, microplankton constitutes 89% of all palynomorphs. About 30% of the latter are represented by *Impagidinium* spp. (12%), *Enneadocysta* spp. (mostly *E. arcuata*) and *Corrudinium incompositum* (7% each), as well as by *Batiacasphaera* spp. (5%, *B. hirsuta* and *B. sphaerica* included). *Operculodinium* spp. (*O. placitum* and *O. tiara* inclusive)

and *Hystrichokolpoma cinctum* are insignificantly abundant (3%). *Rhombodinium pustulosum, Pentadinium* spp. (including *P. taenigerum*), *Spiniferites* spp., *Achomosphaera* sp., *Microdinium* sp., *Deflandrea* spp. (*D. phosphoritica* inclusive), *Melitasphaeridium asterium*, and *Cribroperidinium tenuitabulatum* represent together slightly over 1%. *Achilleodinium* sp., *Apteodinium* sp., *Areoligera* sp., *Cerebrocysta* sp., *Cyclopsiella* sp., *Diphyes colligerum, Dracodinium rhomboideum, Fromea* sp., *Gochtodinium* sp., *Homotryblium plectilum, Lejeunecysta globosa, Lentinia* sp., *Phelodinium* sp., *Pyxidiella* sp., *Rottnestia borussica, Samlandia* sp., *Selenopemphix nephroides, Wetzeliella echinulata*, and *Tytthodiscus beloglinensis* occur as single specimens. The spore–pollen assemblage of the Belaya Glina Formation is less diverse in general than that from the Kuma Formation, because it is confined to deeper facies. It is dominated by *Pinus* spp. and diverse *Tricolpoporopollenites* pollen accompanied by that of *Ephedra* sp., *Podocrapus* sp., Juglandaceae, Fagaceae (mainly evergreen oaks *Quercus graciliformis* and *Q. conferta*) *Rhus* sp., Moraceae, Hamamelidaceae *Myrica* sp., and *Ilex* sp.

Section along the Kuban' River

In the Kuban' River section, the Kuma Formation is exposed 3 km upstream of the bridge that connects Cherkessk with the Psyzh Settlement at the left river side. In total, seven samples from this section were studied. They were taken from the following levels and rock varieties: the transitional member between the Kuma and underlying Keresta formations (Sample 3); brown marls in the middle part of the section (Samples 4 and 5); topmost bed of the member that also bears the leaf flora (one sample); and the lighter member (Samples 6 and 7). The last sample was collected from the bed at the contact with the Belaya Glina Formation. The phytoplankton diversity is usually low (12–15 species), and only samples of brown marly clays and marls with plant impressions from the middle part of the section (Samples 4 and 4a) yield a diverse assemblage (up to 35 species).

The assemblage from the basal part of the section is dominated by *Enneadocysta arcuata* and *Chytroeisphaerida* sp. both representing at least 50% of the phytoplankton. *Impagidinium* sp., *?Cyclopsiella* sp., *Fibrocysta* sp., *Melitasphaeridium* sp., and *Isabelidinium* sp. occur as single specimens. Acritarchs and prasinophytes are represented by *Paucilobimorpha triradiata* and *Ptanospermella* sp. A very peculiar green alga present at this level is conditionally classed with form "A" also common in other sections. The spore–pollen assemblage is 2.5 times more diverse than the phytoplankton. Prevalent is pollen of gymnosperms, particularly that of Fagaceae (*Quercus graciliformis, Q. gracilis, Q.* sp., *Castanopsis* sp.) and *Tricolpoporopollenites* spp. Single grains represent *Corylopsis* sp., *Rhus* sp., Araliaceae, Myricaceae, and *Cornus* sp. Angiosperm taxons are *Pinus* spp. (up to 40%) and *Ephedra* sp. (rare).

In the member of darker marl (Samples 4 and 5), organic matter is particularly abundant. Simultaneously, no fragments of vascular plants are registered. Phytoplankton is noticeably more abundant in the basal part of the member (Sample 4), where it is of a high taxonomic diversity. Most abundant are cysts of *Chytroeisphaerida* sp, green alga (form "A"), and chorate cysts that remained undetermined. In total, they compose up to 70% of the assemblage. Common among other taxons are *Impagidinium* spp., *Enneadocysta arcuata* sp., *Achomosphaera* cf. *sagena, Hystrichosphaeropsis* sp., *Dapsilidinium* sp., and *Cleistosphaeridium* sp. *Leiosphaeridia* sp, *Paucilobimorpha triradiata*, and *Tasmanites* sp. are determined amid green algae and acritarchs. The accessory forms include *Apteodinium* sp., *Cerebrocysta* sp., *Corrudinium incompositum, Cribroperidinium* sp., *Eatonicysta ursulae, Fibrodinium* sp., *Fromea* sp., *Horologinella* sp., *Microdinium* sp., (?)*Riculacysta* sp., *Selenopemphix* sp., *Spiniferites ramosus, Systematophora* sp., *Tectatodinium* sp., *Thalassiophora patula*, and *Wetzeliella "echinulata"*. Composition of the palynological assemblage is similar to that from Sample 3 with one exception: the content of pine pollen increases up to 70%.

Three samples were taken from the upper part of the Kuma Formation. The lower sample was taken from the topmost layer of the dark-colored marly member, where M.A. Akhmet'ev collected leaf impressions of Myricaceae and Fagaceae. The middle and upper samples originate from lighter marls (Sample 6) and from the member transitional between the Kuma and Belaya Glina formations (Sample 7). In the topmost part of the dark-colored member, the diversity of phytoplankton is high (up to 35 species). The main role in the assemblage belongs to *Chytroeisphaerida* sp. Second in abundance are *Trigonopyxida fiscellata, Thalassiophora pelagica, Achilleodinium biformoides, Rhombodinium* spp., *Deflandrea phosphoritica, Spiniferites* spp., *Samlandia* sp., *Cerebrocysta* sp., *Horologinella* sp., *Paucilobimorpha triradiata*, and green alga determined as form "A". Relatively abundant are prasinophytes and acritarchs (up to 30% of the phytoplankton). Subordinate taxons are *Tytthodiscus* sp., *Ptanospermella* sp., *Cymatiosphaera* sp., *Crassosphaera* sp., and the form close to *Krimodiscus* sp. Accessory species characteristic of the Kuma Horizon and occurring as single specimens represent *Alisocysta* sp., *Apteodinium* sp., *Enneadocysta arcuata, Cerodinioum* sp., *Dracodinium condylos, Eisenackia* sp., *Fromea* sp., *Hystrichokolpoma* sp., *Hystrichosphaeropsis* sp., *Impagidinium* sp., *Impletosphaeridinium* sp., *Manumiella* sp., *Melitasphaeridium* sp., *Pentadinium lophophorum, Tectatodinium* sp., *Charlesdowniea coleothrypta, Wetzeliella "echinulata,"* and others. The palynological assemblage typical of the Kuma Horizon is dominated by *Pinus* pollen (65%).

The phytoplankton assemblage from the upper member of the Kuma Formation retains in general the above composition and dominants. Nevertheless, it becomes impoverished and restores its abundance and diversity only in layers transitional to the Belaya Glina Formation. The palynological spectrum slightly dominated by *Pinus* pollen that coexists with the diverse thermophilic phanerogams (small pollen of Fagaceae, *Alfaroa* sp., *Rhus* sp., Araliaceae); associated spores are those of *Gleichenia* and others. At least 30% of the palynological assemblage are represented by *Tricolpoporopollenites* and *Tricolpopollenites* pollen.

The Belaya Glina Formation of the Kuban' section contains an extremely rich assemblage of organic-walled phytoplankton whose diversity in its basal layers (Samples 2 and 9) already exceeds that in the underlying Kuma Formation. The assemblage includes at least 100–120 species and is characterized by a high dispersion coefficient. The Belaya Glina assemblage from the Kuban' species can be considered as a reference one for many other sections of the synonymous formation of the North Caucasus and its age analogues from adjacent platform areas located northerly. Preparations from Sample 9 taken 10 m above the base of the Belaya Glina Formation yielded up to 50–100 specimens of *Microdinium* spp. (including *M. reticulatum*), *Impagidinium* spp. (*I. dispertitum* inclusive), *Thalassiophora* spp. (e.g., *T. pelagica, T. delicata, T. velata, T. reticulata*), *Spiniferites* spp. (*S. pseudofurcatus, S. ramosus*, and *S. cornutus* included), and green algae preliminary classed with the *"Lanjaria"* genus frequent in the Caucasian sections. About 30 taxons are represented by 10 to 50 specimens each. These are *Apteodinium* spp. (*A. emslandense, A. maculatum*), *Enneadocysta arcuata, Areosphaeridium diktyoplokus, Batiacasphaera* spp. (*B. baculata, B. sphaerica*), *Cerebrocysta* sp., *Chytroeisphaeridia* sp., *Cordosphaeridium* spp., (*C. gracile, C. inodes, C. minimum*), *Corrudinium incompositum, Cribroperidinium* spp. (*C. giuseppei, C. tenuitabulatum*), *Dapsilidinium pastielsii, Heteraulacacysta* spp. (*H. pustulata, H. campanula*) *Hystrychosphaeropsis* sp., *Kallosphaeridium* sp., *Operculodinium* spp., (*O. tiara, O. placitum, O. microtrianum*), *Pterodinium* sp., *Rhombodinium* spp. (*R. porosum*) *Samlandia chlamydophora Tectatodinium* sp., and *Micrhystridium* sp. Accessory forms (below 10 specimens) represent more than 50 taxons that commonly occur in the upper Eocene sequences of the Crimea–Caucasus and adjacent platform regions. These are *Achilleodinium biformoides, Adnatosphaeridium multispinosum, Alterbidinium* sp., *Cerebrocysta* sp., *Charlesdowniea coleothrypta, Cleistosphaeridium* sp., cf. *Cyclonephelium* sp., *Dinopterygium cladoides* sensu Morgenroth, *Diphyes colligerum*, cf. *Distatodium* sp., *Eisenackia* sp., *Exochosphaeridium* sp., *Fibrocysta* sp., *Florentinia* sp., *Fromea* sp., *Homotryblium plectilum, Horologinella* sp., *Hystrichokolpoma* spp., (*H. salacium, H. cinc*tum), *Hystrichostrogylon* sp., *Leptodinium* sp., *Lingulodinium* sp., *Melitasphaeridium asterium, Muratodinium* p., *Nematosphaeropsis* sp., *Palaeocystodinium golzowense, ?Palambages* sp., *Paralecaniella indentata, Pentadinium lophophorum, Phthanoperidinium stockmansii, Phth. geminatum, Pyxidiella ?scorbiculata, Rottnestia borussica, Selenopemphix nephroides, Trigonopyxidia fiscellata, Turbiosphaera magnifica, Wetzeliella "echinulata", Wilsonidium ornatum*, and others. Species of the *Paucilobimorpha* genus widespread in the Kuma Formation occur in the Belaya Glina deposits only as single specimens.

In the Kuban' section, the palynological assemblage from the lower part of the Belaya Glina Formation is more diverse than that of the Kuma Formation, though it is inherited, to some extent, from the latter and represents up to 20% of the total amount of palynomorphs. Prevalent is *Pinus* pollen (up to 20%) accompanied by single grains of Taxodiaceae, *Podocarpus* sp., *Sciadopitys* sp., and *Ephedra* sp. The angiosperm group is dominated by pollen of Fagaceae (*Quercus* sp., *Castanopsis* sp., *Castanea* sp.) and *Rhus* sp. Ulmaceae, Araliaceae, and Sapotaceae pollen is present as single grains. Common is pollen of form genera *Tricolpopollenites* and *Tricolpoporopollenites.*

Section along the Kheu River

In the central part of the Greater Caucasus, the Kuma Formation is well exposed in the canyon-shaped valley of the Kheu River near the eastern outskirts of the Gerpegezh Settlement 18 km southeast of Nal'chik. Samples were taken from the section exposed in the canyon (Samples 30–34) and from the upper layers of the formation (Samples 39, 63) in the area, where the river crosses a homocline composed of the Kuma Formation rocks. In contrast to the Kuban' and Belaya River sections, macerates from the Kuma Formation sediments of the Kheu River section show the extremely high contents of amorphous organic matter (up to 96–98%). The other portion of organic matter is represented by palynomorphs. Samples were also taken from the transitional interval between the Keresta and Kuma formations (Samples 30a, 30b, 30c), from the thickest interbed of bentonite clay after volcanic ash (Sample 31a), and from marls underlying the latter at the level separating one third of the formation sequence (Sample 31b). In addition, samples were collected from the middle (Samples 32 and 33) and upper (Sample 63) parts of the formation and from transitional strata between the Kuma and Belaya Glina formations (Samples 34 and 39).

The phytoplankton assemblages from the transitional interval between the Keresta and Kuma formations are uniform except for that of Sample 30b taken directly at the contact between these units. Up to 40% of the phytoplankton from this sample is represented by *Paucilobimorpha tripus* that occurs as single specimens in two other samples from the mentioned interval. Dinocysts in all samples are dominated by *Impagidin-*

ium spp. (*I. maculatum* included) representing up to 20% of the assemblage and by *Areosphaeridium diktyoplokus, Enneadocysta arcuata*, and *Spiniferites* spp. (*S. ramosus, S. cornutus* inclusive). Up to 10–15% of chorate forms remained undetermined. The accessory species (from 3 to 10 specimens) are *Achomosphaera crassipellis, Apteodinium* sp., *Dracodinium* sp., *Leberidocysta* sp., *Operculodinium* sp., and *Wilsonidium echinosuturatum*. Sample 30a taken from the upper layers of the Keresta Formation yielded single specimens of *Achilleodinium biformoides, Alterbidinium* sp., *Areoligera* cf. *senonensis, "Canningia"* sp., *Cerebrocysta* sp., *Chytroeisphaeridia* sp., *Deflandrea* sp., *Hystrichokolpoma* sp., *Hystrichostrogylon* sp., *Impletosphaeridium* sp., *Pterodinium* sp., and *Tectatodinium* sp.

Sample 30b yielded also *Achomosphaera alcicornu, Batiacasphaera* sp., *Dracodinium varielongitudum, Fromea* sp., *Hystrichosphaeridium* sp., *Hystrichosphaeropsis ovum, Lingulodinium* sp., *Phelodinium* sp., *Pterodinium* sp., *Stoveracysta* sp., *Tectatodinium* sp., and *Trigonopyxidia* sp. Preparations from Sample 30c taken in the basal part of the Kuma Formation contain less than 60–70 phytoplankton specimens. In addition to the above-listed dominant forms in common, they show presence of *Achilleodinium biformoides, Achomosphaera* sp., *Caligodnium* sp., *Cerebrocysta* sp., *Chytroeisphaeridia* sp., *Distatodinium* sp., *Fibrocysta* sp., *Melitasphaeridium* sp., *Operculodinium* sp., *Spinidinium* sp., *Systematophora* sp., *Thalassiophora* sp., *Wilsonidium* sp., and *Paucilobimorpha granuligera*.

The extremely high content of prasinophytes and acritarchs is a remarkable feature of the Keresta–Kuma transitional strata. In Sample 30a from the uppermost Keresta Formation, abundance of green alga determined as form "A" is up to 35%. Single specimens of this taxon are also identified in Sample 30b. Other prasinophytes and acritarchs from the last sample are represented by single specimens of *Cymatiosphaera, Ptanospermella*, and *Paucilobimorpha triradiata*.

Marls (Sample 31a) directly underlying the ash bed (Sample 31b) are particularly rich in amorphous organic matter and contain only single specimens of taxons characteristic of the basal part of the Kuma Formation in the Kheu River basin. They yield *Areosphaeridium* sp., *Cerebrocysta* sp., *Chytroeisphaeridia* sp., *Deflandrea* sp., *Impagidinium* sp., *Operculodinium* sp., and *Paucilobimorpha granuligera*. Higher in the section (Sample 32), deposits that are similarly rich in amorphous organic matter enclose abundant thin-walled green alga *"Lanjaria"* and *Chytroeisphaeridia* cysts. These forms associate with very rare representatives of small *Adnatosphaeridium* (6 specimens) and single specimens of *Cerebrocysta* sp., *Cerodinium* sp., *Cordosphaeridium gracile, Cordosphaeridium* sp., *Impagidinium* sp., *Operculodinium* sp., *Rottnestia borussica, Leiosphaeridia* sp., and *Tasmanites* sp.

In the palynological assemblage representing up to 40% of all palynomorphs, shares of *Pinus* and anthophyte pollen are equal. The latter is that of *Quercus gracilis, Q.* sp., *Castanea* sp., *Castanopsis* sp., *Comptonia* sp., *Ilex* sp., *Buxus* sp., *Rhus* sp. (an anther fragment with 7 pollen grains included), *Tetraporina* sp., *Plicapollis* sp., and *Tricolpoporopollenites*.

The amorphous organic matter is particularly abundant (up to 99%) in the middle part of the formation (Sample 33), where phytoplankton is represented by single specimens of *Enneadocysta arcuata, Areosphaeridium diktyoplokus, Distatodinium* sp., *Hystrichosphaeropsis* sp., *Impagidinium* sp., *Melitasphaeridium* sp., *Operculodinium* sp., *Spinidinium* sp., and *Wilsonidium* sp.

Extremely impoverished is a phytoplankton assemblage from upper layers of the Kuma Formation, where amorphous organic matter is still abundant (Sample 63). Only in layers transitional to the Belaya Glina Formation, where amorphous organic matter becomes less abundant, the dinocyst diversity noticeably increases. Sample 63 yielded *Areosphaeridium* sp., *Chytroeisphaeridia* sp., *Impagidinium* sp., *Lentinia wetzelii, Microdinium* sp., *Spinidinium* sp., *Cymatiosphaera* sp., and *"Lanjaria"* sp. Dominant species in Samples 34 and 39, both collected directly at the contact between the Kuma and Belaya Glina formations, are *Enneadocysta arcuata* and *Areosphaeridium diktyoplokus* (up to 15% in sum), and also *Batiacasphaera* and *Spiniferites* forms. These taxons associate with *Chytroeisphaeridia* sp., *Cleistosphaeridium* sp., *Cordosphaeridium gracile, C. inodes, Cribroperidinium tenuitabulatum, Dapsilidinium* sp., *Deflandrea phosphoritica, Fibrocysta radiata, Fromea* sp., *Glaphyrocysta semitecta, Heteraulacacysta campanula, Homotrybium abbreviatum, Hystrichokolpoma cinctum, Impagidinium* spp., *Impletosphaeridium* sp., *Kallosphaeridium* sp., *Lentinia wetzelii, Microdinium* sp., *Melitasphaeridium asterium, Operculodinium* sp., *Pterodinium* sp., *Rottnestia borussica, Spinidinium* sp., *Thalassiophora pelagica, Th. velata, Trigonopyxidia fiscellata, Wilsonidium* sp., and others. The decrease in the content of amorphous organic matter is accompanied by an increase in the dinocyst diversity (up to 25–30 species) and by a noticeable fall of the share of green algae and acritarchs. Only rare specimens of *Crassosphaera* occur in this case.

In the Kheu section, the palynological assemblage from the Kuma Formation is of a low diversity. Angiosperm pollen of Fagaceae (*Quercus, Castanopsis*), *Rhus*, and *Tricolpoporopollenites* of unclear taxonomic position slightly prevails over that of *Pinus*. Araliaceae, Juglandaceae, Myricaceae, *Nyssa*, and others are represented by single pollen grains. Most abundant pollen is detected in the upper part of the Kuma Formation.

The Rostov Salient

North of the Greater Caucasus homocline, lithology of the Kuma Horizon noticeably changes. The rocks are more sandy here and less calcareous. In the Bessergenevskaya area between Rostov and Novocherkassk, the Kuma Horizon that is penetrated by Borehole 571 corresponds to the lower part of the drilled section and underlies the Belaya Glina and Maikop deposits. The section (305 m thick), except for the upper 19-m-thick member of Quaternary sands, is composed of intricately alternating sandy and clayey rocks with abundant glauconite and phosphorite concretions at some levels. Organic-walled phytoplankton occurs through the entire section down to the level of 250 m where the lowermost sample was taken. In total, more than 100 taxons are determined. About 60 of them are recorded in the interval that is correlated with the Kuma Horizon.

Based on the phytoplankton assemblage, the boundary between the Belaya Glina and Maikop deposits is placed at a depth of 94.5 m corresponding to the base of the clayey sand member. It is easily recognizable in the log owing to different specific resistivity of rocks and by replacement of the light-colored Belaya Glina deposits by darker Maikop rocks down in the section. This boundary was drawn at the same level during the initial description of core as well. V.N. Beniamovskii (pers. comm.) who studied benthic foraminifers believes that it corresponds to the depth level of 169 m, and that the middle Eocene strata have not been recovered at all. A.V. Zaitsev and V.G. Pronin let me to be acquainted with the field description of Rostov geologists in whose opinion the middle–upper Eocene boundary corresponds to the base of the argillite member at depth of 137 m.

According to phytoplankton distribution, position of the middle–upper Eocene boundary is ambiguous. It is doubtless that it should be placed within the 50-m-thick interval of the section (254.5 to 204.5 m) composed of clayey–calcareous deposits (argillite-like rocks with glauconite and dispersed nodular phosphorites). Judging from the occurrence of many middle Eocene taxons, the lower 10-m-thick part of this member should be referred to this time interval. Characteristic upper Eocene zonal form *Charlesdowniea clathrata angulosa* first appears in the middle part of the interval and is common in its upper part. Consequently, this interval of the section can be confidently correlated with the upper Eocene. In the log, most significant changes in physical characteristics of rocks are registered at depth of 225 m, and this level can be considered as corresponding to the middle–upper Eocene boundary.

Abundant in the interval of 225–242 m (Samples 41 and 42) and particularly at a depth of 250 m (Sample 43) are *Areosphaeridium diktyoplokus, Enneadocysta arcuata, Cordosphaeridium gracile, Deflandrea oebisfeldensis, Spiniferites* spp., and *Systematophora* spp. (especially *S. placacantha*). These forms associate with *Rhombodinium perforatum* and *Rhombodinium porosum*, the zonal species of the terminal middle Eocene zone, which are also common in the transitional middle–upper Eocene strata of southern Russia. It is remarkable that several other taxons that are usually considered as index species of the middle Eocene dinocyst zones of West Europe are also registered at the same level. Similarly important for referring the lower interval of the phosphorite-bearing argillite member to the middle Eocene is the high diversity of acritarchs and prasinophytes, particularly of *Paucilobimorpha* and large *Micrhystridium* species, the latter characteristic of the Kuma Formation in the Caucasian sections. In addition to the above-mentioned dominant taxons of the middle Eocene interval, samples yielded sufficiently abundant *Charlesdowniea coleothrypta, Corrudinium incompositum, Deflandrea phosphoritica, Impagidinium* spp., *Microdinium reticulatum* (common everywhere in transitional middle–upper Eocene beds and in the basal upper Eocene), *Areoligera coronata, Cribroperidinium tenuitabulatum, Homotryblium plectilum, Samlandia chlamydophora*, and *Thalassiophora pelagica*. Taxons occurring only in the lower part of the section and missing from its upper Eocene and Oligocene intervals are present as single specimens. These are *Deflandrea leptodermata, Dracodinium condylos, Melitasphaeridium* sp., *Pterodinium* sp., and *Spiniferites ramosus. Fromea fragilis, Lejeunecysta globosa*, and *Pyxidiella ?scrobiculata* occur mainly in the lower part of the section. The Rostov section differs from those of the North Caucasus in the absence of two characteristic taxons (*Chytroeisphaeridia* and green algal form "A") that are widespread in the latter.

No substantial changes are observed in spores-pollen assemblages from the considered section as compared with those from the Kuma Horizon of the Greater Caucasus. Spores, pollen, and organic-walled phytoplankton occur approximately in equal proportions. The palynological assemblage is dominated by pollen of *Pinus*, Fagaceae, and *Tricolpoporopollenites*. The upper Eocene interval of the section is also characterized by the extremely low content of spores and pollen (usually less than 10%). In addition to the zonal form *Charlesdowniea clathrata angulosa*, the phytoplankton assemblage includes *Rottnestia borussica, Diphyes colligerum*, and other characteristic late Eocene species. Unusual to some extent is Sample 30 taken at a depth of 174 m, where a half of the phytoplankton assemblage consists of *Glaphyrocysta* sp. Beds with this taxon are defined as an autonomous unit.

Severnye Ergeni

The clayey–marly section drilled by Borehole 45A near the Malye Derbity in the Severnye Ergeni area is lithologically very close to the type section of the Kuma Formation in the Kuma River basin. The Kuma sequence is penetrated here in the interval of 336–325 m. It is separated by hiatuses from both the underlying Cherkessk Formation and overlying Maikop Group. The sequence

is subdivided into two members: the lower one composed of marl and calcareous clay with fish remains, phosphorite nodules, and dispersed pebbles up to 1 cm across at its base, and the upper member represented by greenish gray marl. The members differ in the composition of palynomorphs.

Organic-walled phytoplankton from the lower member represents the *Paucilobimorpha–Horologinella* assemblage. Species of these genera compose more than 50% of the assemblage. Species *Paucilobimorpha triradiata* whose abundance is usually at least 120 specimens per a preparation are main components, and *P. granuligera* is of substantially lower abundance. In the dinocyst assemblage, the main role belongs to species of *Areosphaeridium, Deflandrea, Enneadocysta*, and *Microdinium* genera (*A. diktyoplokus, E. arcuata, E. ?pectiniformis, D. arcuata, D. phosphoritica, D. oebisfeldensis, D.* sp. "A", and *M. reticulatum*). Accessory elements that occur as single specimens are represented at least by 50 taxons, present among which are *Apectodinium longispinosum, A.* cf. *A. maculatum, Charlesdowniea coleothrypta, Cordosphaeridium gracile, C. inodes, Dracodinium* cf. *D. condylos, Fibrocysta* sp., *Heteraulacacysta pustulata, H.* sp., *Hystrichosphaeropsis* sp., *Hystrichostrogylon* sp., *Impaginidium* sp., *Lingulodinium* sp., *Melitasphaeridium* sp., *Rottnestia borussica, Samlandia chlamydophora, Spinidinium* sp., *Spiniferites* spp. (*S. ramosus, S. cornutus, S. pseudofurcatus*), and *Wetzeliella articulata.* Species *Ptanospermella* and *Micrhystridium* are present amid acritarchs and prasinophytes. Comparison with the Rostov assemblage shows that the Kuma deposits of the Ergeni area contain more than a half of taxa in common, although characteristic North Caucasian dominant forms, such as *Chytroeisphaeridia* and green algal form "A," are missing here.

The content of gymnosperm pollen (up to 10%) in palynological assemblage from the Kuma deposits is lower than in underlying strata. Gymnosperms are mainly represented by *Pinus* and, less commonly, by Taxodiaceae, and *Ephedra.* The dominant role belongs to pollen of Fagaceae (*Quercus gracilis, Q, graciliformis, Q. conferta*). Samples 131 and 127 contain abundant pollen of *Castanopsis* sp., Myricaceae, and *Rhus* sp. Pollen of form taxons (probably reworked) is represented by *Plicapollis* sp., *Triporopollenites* spp. (*T.* cf. *T. megagranifera* included), *Tricolpoporopollenites* spp., *Trudopollis pompeckii, Rhoipites* sp., and *Triatriopollenites* sp. (up to 30% in total). Pollen of thermophilic plants corresponds to Juglandaceae (*Alfaroa* sp., *Engelhardtia* sp.) and associated Palmae, Araliaceae, *Comptonia minima, Corylopsis* sp., and *Liquidambar* sp.

The age of the Kuma deposits in the Ergeni section can be determined by comparing their phytoplankton assemblages with those from West European sections, where they include abundant *Paucilobimorpha* and *Horologinella* species characteristic of the upper Lutetian and Bartonian strata of the southern Netherlands and Great Britain (De Coninck, 1986). The Bartonian age of the considered deposits is also substantiated by presence of many species characteristic of the dinocyst *Rhombodinium perforatum–Rhombodinium porosum* Zone (Costa and Manum, 1988) in the phytoplankton assemblage from the upper member.

Voronezh Anteclise

The organic-walled phytoplankton assemblages, which are compositionally very similar to those from the Kuma Horizon of the North Caucasus and its age analogues in the East European platform and Scythian plate, were distinguished in sections drilled by Boreholes 7250 and 7252 in the southern flank of the Voronezh anteclise near the town of Novyi Oskol. Below the Zmievka(?) Beds of the Oligocene, there is the sandy–silty Derezovka Formation overlying the clayey–marly member. This member is referred to the Kiev Formation, which, in turn, rests on the erosional surface of the Buchak Sands. The Derezovka Formation is 8.0 and 19 m thick in Boreholes 7250 (interval of 30.3–23.5 m) and 7252 (interval of 51.0–32.0 m), respectively. This subdivision of the section was recognized by N.P. Tazov who headed drilling works. Yu.I. Iosifova followed initially his scheme, but later on she referred (pers. comm.) all the Eocene deposits, from which samples were taken, to the Kiev Formation. In this paper, I follow the scheme by Tazov who donated samples for my analysis.

The Kiev Formation 8.7 m thick was penetrated in Borehole 7250 within the interval of 39.0–30.3 m. Sample 9 was taken from this unit at a depth of 32.0 m. In Borehole 7252, the formation recovered in the interval of 60.5–51.0 m is 9.5 m thick. Sample 18 was taken at a depth of 60.0 m. Samples from the Derezovka Formation were collected at the depth levels of 28.0 (Sample 7) in Borehole 7250 and of 34.0, 34.6, 35.0, 37.0, 45.0, and 49.0 m (Samples 8, 5-1, 6-1, 7-1, 12, and 9-1, respectively) in Borehole 7252. The phytoplankton assemblage of the Kiev Formation consists of species buried *in situ*, whereas that from the Derezovka Formation is mixed and includes abundant reworked forms complicating interpretation of phytoplankton composition. It is also unfortunate that the boreholes were drilled using the cleansing solution prepared with addition of the Kiev Formation clays.

The phytoplankton assemblage from the Kiev Formation is dominated by species of the *Paucilobimorpha* and *Horologinella* genera (over 50% together). In Sample 18 from Borehole 7251 taken from the basal part of the section, *Paucilobimorpha granuligera, P. triradiata, P. tripus*, and *P.* sp. are particularly abundant. The assemblage from Sample 9 (Borehole 7252) is dominated by *P. triradiata* (up to 75%) accompanied by *Horologinella* sp. (12%), and *P. tripus* (6%). Amid other taxons, the noticeable role belongs *Enneadocysta* spp. (particularly *E. arcuata, Deflandrea* spp. (*D. phosphoritica* included), *Microdinium* sp., and *Wetzeliella*

articulata. Occurring as single specimens (up to 3) are *Achilleodinium biformoides, Areosphaeridium dictyoplokus, Cribroperidinium* sp., *Dapsilidinium* sp., *Deflandrea heterophlycta, Melitasphaeridium* sp., *Samlandia* sp., *Spinidinium* sp., *Spiniferites* sp., and *Tectatodinium* sp. Acritarchs and prasinophytes are represented by *Crassosphaera* sp., *Cymatiosphaera* sp., and *Micrhystridium* sp. Composition of the phytoplankton assemblage from the clayey–marly member with abundant *Paucilobimorpha triradiata, P. tipus*, and others taxons in common with those from the upper member of the Keresta Formation in the Kheu River basin gives grounds to correlate the studied upper part of the Kiev Formation with that formation. The spores-pollen assemblage from the Kiev Formation is impoverished and includes single specimens of *Platycarya, Quercus graciliforms, Castanopsis pseudocingulum*, and pollen of form genera.

Phytoplankton from the Derezovka Formation is diverse and abundant probably owing to presence of reworked forms. It total, it includes over 180 taxons and is characterized by the high dispersion coefficient. Palynomorphs are particularly abundant in the interval of 35.0–37.0 m in Borehole 7252 corresponding to the upper part of the formation. Although the assemblage retains the dominant taxons of the Kiev Formation (in particular, *Paucilobimorpha triradiata, P. tripus, P. granuligera*, and *Microdinium*), the role of other important species changes. For instance, the role of *Deflandrea* spp. (*D. oebisfeldensis, D. heterophlycta, D. phosphoritica*), *Wetzeliella–Charlesdowniea* group (*W. ovalis, W. articulata, W. "echinulata", Ch. coleothrypta, Ch. coleothrypta* f. *rotundata*), *Spiniferites* spp., *Enneadocysta* spp., *Heteraulacacysta pustulata, Achomosphaera* sp., and *Systematophora placacantha* substantially increases. Also present are species of the *Batiacasphaera* and *Pentadinium* genera. Taxons occurring as 5 to 20 specimens are *Cordosphaeridium* sp., *Cribroperidinium tenuitabulatum, Diphyes* spp., (*D. ficusoides, D. colligerum*), *Fromea* sp., *Glaphyrocysta* sp., *Heteraulacacysta* spp. (*H. porosum*), *Horologinella* sp., *Hystrichokolpoma cinctum, Operculodinium tiara, Phthanoperidinium stockmansii, Samlandia chlamydophora, Thalassiophora pelagica*, and *Micrhystridium* sp.

In Borehole 7250 (Sample 7-1, depth of 37 m), sediments in the upper part of the section enclose the assemblage of single *Chytroeisphaeridia* sp. and *Rhombodinium* spp. (*Rh. perforatum* included), *Achilleodinium biformoides, Alterbidinium* sp., *Cerodinium* spp., *Cordosphaeridium funiculatum, C. inodes, Dapsilidinium pastielsii, Eisenackia* sp., *Florentinia* sp., *Impagidinium* spp., *Melitasphaeridium asterium, Palaeocystodinium golzowense, Phelodinium* sp., *Rottnestia borussica, Spinidinium* sp., and *Tectatodinium* sp. According to presence of one zonal species, this phytoplankton assemblage can be attributed to the *Rhombodinium perforatum–Rhombodinium porosum* Zone (the second half of the Bartonian to, probably, basal Priabonian). It should be emphasized only that the characteristic zonal Priabonian form *Charlesdowniea clathrata angulosa* is missing from the Derezovka Formation in the considered section. Similarly to the palynological assemblage from the Kiev Formation, that from the Derezovka Formation is highly impoverished and includes single pollen grains of *Pinus, Castanopsis, Quercus (Q. graciliformis), Engelhardtia*, and others. In total, the pollen content is below 5% in the phytoplankton assemblage.

Turan Plate

In the Turan plate, age analogues of the Kuma Formation are established at the base of the stratotype section of the Chegan Formation in the chinks of the Ustyurt Plateau (Mt. Sandal). The siltstone member with the *Rhombodinium perforatum–Rhombodinium porosum* phytoplankton assemblage of the upper Bartonian is confined to the upper part of the Saksaul'skaya Formation that is overlain by the Chegan Formation beginning with the bed of phosphorite nodules. *Charlesdowniea clathrata angulosa*, the index species of the upper Eocene, appears as single specimens in the clayey member of the Chegan Formation directly below the phosphorite layer. The apparent thickness of the Saksaul'skaya Formation in the Mt. Sandal section does not exceed 5 m.

The diverse phytoplankton assemblage from the Saksaul'skaya Formation represents 70–80% of all palynomorphs and includes at least 60 species. The leading role in the assemblage belongs to *Microdinium reticulatum, Deflandrea phosphoritica, D. heterophlycta, Rhombodinium perforatum, Rh. longimanum*, to various representatives of the *Wetzeliella* group (particularly *Charlesdowniea coleothrypta* and *Ch. coleothrypta* f. *angulata*), and to species of the *Spiniferites, Areosphaeridium, Enneadocysta, Pentadinium, Thalassiophora, Cordosphaeridium, Cyclonephelium, Heteraulacacysta*, and other genera. In contrast to all westerly sections, prasinophytes and acritarchs, except *Crassosphaera* and *Paucilobimorpha triradiata*, are recorded as single specimens in the area under consideration. Species of the *Wetzeliella* group and *Deflandrea* genus become main components of the phytoplankton assemblage in the Chegan Formation. Common are also *Areosphaeridium* sp., *Enneadocysta* sp., *Dinopterygium* sp., *Phthanoperidinium* sp., and *Rhombodinium* sp. Amid green algae, prevalent are taxons characteristic of warm-water sea basins with the normal salinity (*Crassosphaera* sp., *Tytthodiscus* sp. *"Lanjaria"* sp.).

The palynological assemblage from the Saksaul'skaya Formation is dominated by pollen of thermophilic angiosperms *Castanopsis* sp., *Quercus conferta, Q. sparsa, Q. gracilis, Q. graciliformis, Platycarya* sp., Moraceae, *Corylopsis* sp., Palmae, and Myrtaceae. Pollen of *Pinus* represents less than 20%. Present is reworked pollen of *Trudopollis pompeckii*.

The spore–pollen assemblage from the stratotype section of the Chegan Formation, where the latter is correlated, based on phytoplankton, with the *Charlesdowniea clathrata angulosa* Zone, shows a high share of conifers, particularly of *Pinus*, retaining the former role of thermophilic angiosperms. New components are represented by pollen of Juglandaceae, Moraceae, Hamamelidaceae, *Nyssa*, and *Rhus*.

DISCUSSION

The analysis of palynomorphs from the Kuma Formation and its age analogues in vast regions of southern Russia provided an opportunity to reveal some regularities in compositional changes of phytoplankton and palynological assemblages, and to understand their individual features controlled by ecological factors, such as facies and climatic depositional environments, basin hydrology, position of the studied area relative to the ancient shoreline, and others. Compositional changes of palynological assemblages that depended on the age of enclosing deposits were also noted. Of a particular interest is the analysis of proportions between the dispersed amorphous organic matter, palynomorphs, and fragments of terrestrial plant tissue, as well as the study of structure of palynological taphocoenoses. I mean first of all the taphocoenoses from sequences formed in the anoxic setting, which distinctly show the mono- and polytypic composition of the assemblages. Also important was the analysis of dynamics of compositional changes in palynological assemblages confined to different facies.

It seems reasonable to start consideration the abovementioned problems with the analysis of distribution of palynomorph and amorphous organic matter in the Kuma Formation beds, where this matter is a main constituent of macerates. Its content in samples approximately equal in volumes (3–5 cm^3) is by an order and more higher in the North Caucasian sections. Different modifications of organic matter were distinguished. It is most frequently dispersed, or sometimes forming aggregates that are particularly characteristic of the upper transitional member. The highest content of amorphous organic matter was observed in dark-colored rock varieties, in which phytoplankton, spores, and pollen constitute together less than 5% of the macerate volume, and the decrease in the dinocyst taxonomic diversity is partly compensated by the mass occurrence of prasinophytes and Chytroeisphaeridia like in marls saturated with sulfides and fish debris. This was noted in samples from the Kheu and Kuban' sections. In the section along the Belaya River, the share of amorphous organic matter is generally lower, and I think that we deal in this case only with the upper part of the Kuma Formation that formed under the weakened stagnation regime.

The abundance of palynomorphs and fragments of vascular plants also varies. The share of both components in darkest rock varieties is usually below 1%. In such rocks, organic-walled phytoplankton, pollen, and spores occur in equal proportions, whereas fragments of cuticular tissue are almost missing. In rocks of lighter coloration, the content of amorphous organic matter gradually decreases, and when this matter represents about 50% of the macerate, i.e., is balanced with the content of palynomorphs, the ratio between organic-walled phytoplankton, on the one hand, and spores and pollen, on the other, is also equal at first. Parallel to this, fragments of terrestrial plant fragments appear. Proportions between main constituents of macerates substantially change in white marls and clays, in which the content of amorphous organic matter is negligible, whereas the organic-walled phytoplankton prevails over palynomorphs of higher plants and may represent up to 90–95% of macerates. This is a persistent characteristic of rocks of the Belaya Glina Formation.

Outside the North Caucasus, the role of dispersed amorphous organic matter in sediments coeval to the Kuma Formation becomes insignificant, and this, as we will see below, is accompanied by compositional changes in palynological assemblages. Moreover, spores, pollen, and organic-walled phytoplankton are either equally abundant, or the latter slightly prevails and simultaneously is more diverse. The monotypic composition of assemblages is still retained, though being less expressed, but what is more important, it is most likely caused by variations in the basin salinity. Remarkable as well is the analyzed composition of dominant taxons in assemblages, in particular when the latter are mono- or polytypic. To demonstrate this, let us return to the analysis of assemblages established in particular sections.

In the lower part of the *Belaya River section*, where a hiatus corresponds to the early Kuma time, *Areosphaeridium diktyoplokus* and *Microdinium reticulatum* are dominants. Next in abundance are *Enneadocysta arcuata*, *Impagidinium* sp., and *Chytroeisphaeridia* sp. In layers transitional to the Belaya Glina Formation, the last of these species disappears, whereas others continue to be dominant in the assemblage.

Like in the Belaya River section, the phytoplankton assemblage from the basal layers of the *Kuban' River section* is dominated by species *Enneadocystsa* (*E. arcuata*) and *Chytroeisphaeridia* genera. In the member of dark-colored marls corresponding to the middle part of the section, the leading role belongs to prasinophytes (form "A") and to *Chytroeisphaeridia*. Distinctly subordinate but rather common are *Achomosphaera* cf. *sagena*, *Cleistosphaeridium*, *Dapsilidinium*, and *Impagidinium*. In the upper part of the formation, where abundance of prasinophytes is reduced, *Chytroeisphaeridia* is still dominant, but even this species completely disappears in layers transitional to the Belaya Glina Formation. Simultaneously, *Trigonopyxidia fiscellata*, *Thalassiophora pelagica*, *Achilleodinium biformoides*, *Rhombodinium* sp., *Deflandrea phosphor-*

itica, Areosphaeridium, Samlandia, Cerebrocysta, Horologinella, and *Paucilobimorpha* become more abundant. The Belaya Glina Formation is characterized by a more stable group of dominant taxons that includes *Impagidinium, Spiniferites, Thalassiophora*, and *"Lanjaria."*

In the *Kheu River section*, composition of dominant species is generally the same as in the Kuban' River section, although it repeatedly changes with the narrow time range of basal layers. In the upper Keresta Formation, *Impagidinium* (*I. maculatum*) and green alga form "A" occur in abundance. Common, though subordinate here, are *Achomosphaera crassipellis, Enneadocysta arcuata, Spiniferites* spp., and *Wilsonidium echinosuturatum.* Species *Paucilobimorpha* appears in the section to become dominant, along with *Impagidinium*, only a few centimeters above the boundary between the Kuma and Keresta formations. Next in abundance is a group of *Areosphaeridium* spp., *Dracodinium varielongitudum, Spiniferites* spp., and *Wilsonidium echinosuturatum.* In the basal layers of the Kuma Formation, the new member among dominant taxons is *Achilleodinium biformoides.* The middle part of the section that was accumulated in highly anoxic environments is characterized by a sharply reduced diversity of phytoplankton. The dominant elements in the assemblage are *Chytroeisphaeridia* and *"Lanjaria."* In layers transitional to the Belaya Glina Formation, these species are missing, and the leading role passes, like in other North Caucasian sections, to *Enneadocysta arcuata, Areosphaeridium diktyoplokus, Spiniferites* sp., and *Batiacasphaera* spp.

In the North Caucasian sections, phytoplankton assemblages from alternating members of dark- and light-colored marls show the repeated restoration of their spectra. This emphasizes an ecological, not evolutionary cause of changes in composition of the organic-walled phytoplankton.

In the *Rostov salient section*, the phytoplankton assemblage from the uppermost middle Eocene is characterized by the high diversity and dispersion coefficient, so that discrimination of dominant taxons is complicated. Its dominant group includes *Enneadocysta arcuata, Cordosphaeridium gracile, Impagidinium* spp., *Spiniferites* spp., *Systematophora placacantha*, and *Paucilobimorpha triradiata.* Taxons that are more characteristic of the middle–upper Eocene boundary interval, such as *Areosphaeridium diktyoplokus, Corrudinium incompositum, Microdinium* spp., and *Rhombodinium perforatum* occur at the same level.

In the *Severnye Ergeni section*, the Kuma Formation encloses the monotypic phytoplankton assemblage with the absolute prevalence of Horologinella and Paucilobimorpha. The last genus is represented by three main species (*P. triradiata, P. tripus, P. granuligera*) that are accompanied by *Rhombodinium* forms. Other important taxons are *Impagidinium, Areosphaeridium* spp., *Cordosphaeridium gracile*, and *C. funiculatum.* Noticeably more representative becomes the *Wetzeliella* group accompanied by *Rhombodinium. Chytroeisphaeridia* forms occur as single specimens. This taxon is useful for correlation of the Kuma Horizon.

The dinocyst assemblage from the *Voronezh anteclise section* is compositionally closer to the assemblage from the Ergeni section than to that from the Rostov salient. Like in the Ergeni section, the dinocyst assemblage from the Kiev and Keresta formations and from basal layers of the Kuma Formation of the North Caucasus is dominated by *Horologinella* spp., *Paucilobimorpha tripus*, and *P. triradiata.* These taxons are accompanied by *Areosphaeridium, Deflandrea, Microdinium* forms, and by *Wetzeliella angulata.* In the highly diverse assemblage from the Derezovka Formation (over 100 taxons), the mentioned dominant components retain their position, but *Wetzeliella, Deflandrea, Enneadocysta, Spiniferites, Achomosphaera, Systematophora*, and *Heteraulacacysta* simultaneously become the leading components. In some samples, *Rhombodinium, Chytroeisphaeridia, Dracodinium, Melitasphaeridia asterium, Operculodinium tiara, Achomosphaera crassipellis, Systematophora placacantha*, and other taxons characteristic of the Kuma Horizon are rather abundant (up to 10 specimens).

In the upper middle Eocene assemblage from the *Turan plate section*, the group of dominant forms includes species of the *Wetzeliella, Charlesdowniea, Rhombodinium, Microdinium*, and *Deflandrea* genera.

The presented data on dominant taxons, which should be considered as ecological groups, are used to outline their distribution areas and to interpret their habitat. Prasinophytes (form "A") and *Chytroeisphaeridia* are confined to sediments that formed in reducing environment of the North Caucasian Kuma basin. It is probable that they are indicators of the so-called red tides that originate from the intense development of some highly toxic taxons responsible for the mass death of fishes and other biotic groups. However, it is similarly probable that these taxons could develop in abundance within the water layer thicker than that of the photic (s. str.) zone. It is likely that their habitat could extend down to the upper part of the H_2S-contaminated zone. In the areas where the anoxic regime disappeared or was replaced by the aerobic one, abundance of these taxons sharply deceased. Such a recurrence is characteristic not only of organic-walled phytoplankton, but of foraminifers as well (Bugrova, 1988). Simultaneously, the uppermost oxygen-saturated zone of the photic layer was occupied by many other species typical of middle Eocene basins with the normal salinity. The different composition of late Kuma assemblages, as compared with those from the lower Eocene deposits, could be to some extent a consequence of cooling, though it was mostly controlled by evolutionary development of phytoplankton. In the platform part of the basin that stretched from the Ergeni area to the Voronezh anteclise, the prevalence of *Paucilobimorpha* and *Horologinella* species also points to the anomalous ecological environments that disap-

peared in the Belaya Glina time. However, this was caused rather not by water freshening in the near-shore zone of the basin, as some researchers believe, but by some other factors, because the indicated taxons are accompanied by many dozens of species typical of normal marine environments. The phenomenon of mass development of these taxons in the basin needs an adequate explanation. One of possible explanations is a kind of nutrients entering the basin. Finally, intervals of the section, where the *Wetzeliella* group, *Deflandrea, Microdinium, Rhombodinium*, and newly appearing *Micrhystridium* are significant taxons, accumulated most likely in the estuarine setting of the near-shore zone. This assumption is compatible with general paleogeographic situation as it is reconstructed for the second half of the middle Eocene.

Despite compositional differences in dominant groups of taxons, phytoplankton assemblages from all studied sections include species representing the core of the Kuma assemblage and occurring, although sometimes as single specimens, over a spacious territory. Some of them either appeared or disappeared in the Kuma time. These are *Achilleodinium biformoides, Achomosphaera crassipellis, A. alcicornu, Apteodinium maculatum, Enneadocysta arcuata, Areosphaeridium diktyoplokus, Batiacasphaera* spp., *Caligodinium* sp., *Cerebrocysta* sp., *Cerodinium diebelii, Cordosphaeridium gracile, Corrudinium incompositum, Cribroperidinium tenuitabulatum, Deflandrea oebisfeldensis, Diphyes colligerum, Dracodinium condylos, Fibrocysta* sp., *Fromea* sp., *Heteraulacacysta* spp., *Hystrichokolpoma* spp., *Impagidinium* sp., *Impletosphaeridium* sp., *Melitasphaeridium asterium, Microdinium reticulatum, Operculodinium tiara, Phelodinium* sp., *Pterodinium* sp., *Pyxidiella ?scorbiculata, Rottnestia borussica, Samlandia chlamydophora, Spinidinium* sp., *Spiniferites* spp., *Systematophora placacantha, Tectatodinium* sp., *Thalassiophora pelagica, Trigonopyxidia fiscellata, Wetzeliella "echinulata," Wilsonidium echinosuturatum*, and others.

In the most complete sections (Kuban', Kheu, Novyi Oskol), two groups of taxons corresponding to the lower and upper parts of the Kuma Formation can be distinguished. The first of them includes *Paucilobimorpha tripus, Chytroeisphaeridia* sp., *Areosphaeridium diktyoplokus, Cerodinium diebelii, Cordosphaeridium gracile, Corrudinium incompositum, Deflandrea oebisfeldensis, Dracodinium condylos, Operculodinium tiara, Pterodinium* sp., *Phelodinium* sp., *Pyxidiella ?scorbiculata*, and *Pyxidiella ?scorbiculata*. The upper part of the formation is characterized by a wider development of species from the *Wetzeliella, Charlesdowniea*, and *Microdinium* groups. The diverse *Deflandrea* species commonly coexist at this level with *Rottnestia borussica, Samlandia chlamydophora*, and *Rhombodinium* forms. The last genus is represented by *Rhombodinium perforatum* and *Rh. porosum*, the zonal species of the upper Bartonian substage. All these species continued to exist also at the beginning of the late Eocene.

CONCLUSION

In the northern periphery of the Tethyan basin of eastern Europe and western Kazakhstan, the organic-walled phytoplankton of the second half of the middle Eocene was extremely diverse, consisting of 250 species at least. One hundred fifty most characteristic of these species are listed in the Table.

Variations in composition of phytoplankton assemblages were mainly controlled by changes in the hydrological regime of the basin rather than by climatic zoning. The cooling phase of the terminal Bartonian was responsible for the greater share of cavate dinocysts of the *Rhombodinium* and *Deflandrea* genera. In the littoral and inner shelf zones, as well as above some rises of the outer shelf, a considerable part of phytoplankton consisted of prasinophytes and acritarchs. During the anoxic episodes that frequently, particularly in the early Bartonian, corresponded to the phases of volcanic activity, composition of phytoplankton assemblages changed also in the inner part of the sea basin.

Taking into consideration distribution of the abovementioned taxons through the studied sections, one can define their stratigraphic position in the standard chronostratigraphic scale of the Eocene and in the regional stratigraphic scale that includes the Kuma Horizon. The section along the Belaya River corresponds most likely to the upper Bartonian only. The same position is characteristic of deposits studied in the Rostov salient and northern Ustyurt Plateau. In the Severnye Ergeni section, the lower member of the Kuma Formation is attributed to the lower Bartonian, whereas the upper one undoubtedly should be referred to the upper Bartonian. Upper layers of the Kiev Formation in the Voronezh syneclise correspond not only to lower beds of the Kuma Formation, but to the Keresta Formation as well. In its upper part, the Derezovka Formation is transitional between the middle and upper Eocene.

The Kuma Horizon can be subdivided into two dinocysts zones. The lower one that was formerly distinguished as the *Areosphaeridium diktyoplokus* Zone (Zaporozhets, 1999), should now be termed, taking into consideration the new data, as the *Areosphaeridium diktyoplokus–Dracodinium condylos* Zone. It is a complete equivalent of the *Dracodinium intermedium–Areosphaeridium diktyoplokus* Zone established by Andreeva-Grigorovich (1991) as an autonomous unit (D9) of the regional scale accepted in the former USSR. It is hardly reasonable to retain *D. intermedium* in the zone name, because this species is not valid. Simultaneously, there are no doubts that the studied cysts should be attributed to *D. condylos*. The Keresta Formation of the North Caucasus is also correlative with the same zone, and the probable late Lutetian age of some part of this zone is therefore not inconceivable. Some differences in composition of dinocyst assemblages from the upper and lower parts of the *Areosphaeridium diktyoplokus–Dracodinium condylos* Zone imply that it can be divided into two autonomous

Distribution of organic-walled phytoplankton in the Kuma Horizon of Northern Caucasus and its age analogues in the East European platform, Scythian and Turan plates

Species	Upper Lutetian–initial Bartonian			Bartonian					Upper Bartonian–initial Lutetian						
	Archaejsphaeridium diktyoplokus–Dracodinium condylos Zone								*Rhombodinium perforatum–Rhombodinium porosum* Zon						
	layers transitional from the Keresta Formation to the Kuma Formation			Kuma Formation (main part)					upper part of the Kuma Formation and layers transitional to the Belaya Glina Formation						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Dinocysts															
Achilleodinium biformoides		+	+		+			+						+	
Achomosphaera alcicornu		+													
A. diktyoplokus	+	x	x	x	+	o	+	+		+		+	x	+	+
Adnatosphaeridium multispinosum										+					+
Adnatosphaeridium sp.				+		+									
Alterbidinium sp.	+									+				+	
Apteodinium maculatum	+						+			+		+			
Apteodinium spp.	+				+				+	+		+	+		
Caligodinium sp.		+			+										
Cerebrocysta sp.	+			+	+	+	+		+	+		+			
Chytroeisphaeridia sp.		+	+	+	m	+	+	+		+	o	+	+		
Deflandrea sp.		+		+		+	+	x	+	+		+		x	m
Distatodinium sp.		+				+				+					
Dracodinium condylos		+	+		+							+			
D. varielongitudum			+												
Enneadocysta arcuata	o	+	o	x	x	x	+	x	x	x	x	o	+	x	x
Fibrocysta sp.		+			+					+			+		
Horologinella sp.	+	+	o	+	+	+	m	x	o	x		+	o	+	+
Hystrichokolpoma sp.			+			+				+		+			
Hystrichostrogylon sp.			+							+		+			+
Impagidinium maculatum		+													
Impagidinium sp.	+	x		x	+	+	o	+	+	x	+	o	+	+	+
Isabelidinium sp.	+														
Melitasphaeridium sp.	+		+		+	+			+	+		+			
Operculodinium sp.		+		+		+			+	+	+	x			o
Pterodinium sp.		+		+		+			+	+	+	+			
Rottnestia borussica		+		+		+			x	+	+	o	+		
Spinidinium sp.			+			+				+	+		+		+
Spiniferites cornutus		+					+			+		+			
S. ramosus		+				+								+	
Spiniferites sp.		+	+	+	+	+	+	+	+		+	+	+	+	+
Systematophora sp.		+		+	+							o			x
Tectatodinium sp.		+	+	+	+		+		+	+	+	+	+	+	+
Thalassiphora sp.		+							+	+				+	+
Trigonopyxidia fascellata		+							+	+	+				+
Wilsonidium echinosuturatum		+							+						

Table. (Contd.)

Species	Upper Lutetian–initial Bartonian			Bartonian					Upper Bartonian–initial Lutetian						
	Archaejsphaeridium diktyoplokus–Dracodinium condylos Zone								*Rhombodinium perforatum–Rhombodinium porosum* Zon						
	layers transitional from the Keresta Formation to the Kuma Formation			Kuma Formation (main part)					upper part of the Kuma Formation and layers transitional to the Belaya Glina Formation						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Wilsonidium sp.		+				+						+			+
Prasinophytes and acritarchs															
Crassosphaera sp.			+	+	+		+		+	+			+	+	x
Paucilobimorpha granuligera		x	m	+	+	x	m		+	+	+	+	+	x	
P. triradiata	+	x	m		x		o	o		x		m	x	x	x
P. tripus		m	m			+	+	m				+	+	+	
Ptanospermella sp.	+			+	+		+		+	+		+	+		+
Forma "A"	+	m			x	+									
Dinocysts															
Achomosphaera cf. *sagena*					+										
Areosphaeridium sp.				x	+	+	+	o	x		+	x	x	o	x
Batiacasphaera baculata								+				+	+	+	
B. sphaerica				+					x	+				+	
Cerodinium diebelii				+							+				
Cerodinium sp.				+						+			+		
Charlesdowniea clathrata								+					x		x
Ch. coleothrypta					+			+		+		+	x	x	o
Ch. coleothrypta subsp. *rotundata*								+				+		+	o
Cleistosphaeridium sp.				+	+					+	+		+		
Cordosphaeridium gracile						+				+	+	o	+		+
C. exilimurum				+											
C. funiculatum				+		+	+					+	+	+	x
C. latispinosum															+
Corrudinium incompositum				+					x	+	x				+
Cribroperidinium tenuitabulatum				+			+	+		+	+	+	+	+	
Cribroperidinium sp.				+						+		x			
Cyclopsiella sp.				+						+					
Dapsilidinium simplex				+								+			+
Dapsilidinium sp.				+	x			+		+	+	x			
Deflandrea oebisfeldensis							+					x	+		
Dinopterygium cladoides							+								+
Diphyes colligerum				+				+		+	+				
Dracodinium rhomboideum				+					+			+	+		
Dracodinium sp.						+	+								+
Eatonicysta ursulae				+											
Eisenackia sp.					+					+					
Glaphyrocysta ?vicina							+								
Heteraulacacysta ?leptalea				+											o

Table. (Contd.)

Species	Upper Lutetian–initial Bartonian			Bartonian					Upper Bartonian–initial Lutetian						
	Archaejsphaeridium diktyoplokus–Dracodinium condylos Zone								*Rhombodinium perforatum–Rhombodinium porosum* Zon						
	layers transitional from the Keresta Formation to the Kuma Formation			Kuma Formation (main part)					upper part of the Kuma Formation and layers transitional to the Belaya Glina Formation						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
H. pustulata				+			+			+					+
Hystrichokolpoma cinctum							+	+		+	+		+		
Hystrichosphaeropsis sp.				+	+	+				+		+			+
Impletosphaeridium sp.		+		+	+					+					
Lejeunecysta globosa				+					+			+			
Lingulodinium sp.							+			+		x	x		+
Manumiella sp.				+	+										
Melitasphaeridium asterium				+						+	+	+	+		
Microdinium reticulatum				+				m	+	x		x	x	m	m
Microdinium sp.				x	+	+		m	+	x	+	x	+	m	m
Palaeocystodinium golzowense							+			+		+	+	+	+
Paralecaniella indentata				+						+					
Pentadinium laticinctum							+				+				
P. lophophorum				+			+		+						x
Pentadinium sp.				+	+			+	+			+		+	+
Phthanoperidinium stockmansii							+	+		+		+			+
Phthanoperidinium sp.				+	+			+	+	+		+		+	+
Pyxidiella ?scrobiculata								+				+			+
Rhombodinium draco				+											
Rhombodinium sp.				+	+				+	+					+
Samlandia chlamydophora					+		+	+	+	+	+	+	+	+	+
S. reticulifera								+							
Selenopemphix nephroides				+						+		x	+	+	+
Spiniferites pseudofurcatus							+	+		+		+	+	+	+
Systematophora placacantha							+					x	+		+
Thalassiphora patula				+											+
Th. pelagica				+	+			+	x	+	+	+		+	+
Wetzeliella articulata							+	+					+	+	+
W. "echinulata"				+	+			+	+	+				+	+
Prasinophytes and acritarchs															
Cymatiosphaera sp.				+	+	+	+	+				+	+	+	+
"*Lanjaria* sp."						m				+				m	
Leiosphaeridia sp.				+	+	+									
Tytthodiscus sp.					+				+					m	
Micrhystridium sp.							x	x		+		x	+	x	x
Pediastrum sp.								+							+
Tasmanites sp.					+	+									

Table. (Contd.)

Species	Upper Lutetian–initial Bartonian			Bartonian					Upper Bartonian–initial Lutetian						
	Archaejsphaeridium diktyoplokus–Dracodinium condylos Zone								*Rhombodinium perforatum–Rhombodinium porosum* Zon						
	layers transitional from the Keresta Formation to the Kuma Formation			Kuma Formation (main part)					upper part of the Kuma Formation and layers transitional to the Belaya Glina Formation						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Dinocysts															
Achomosphaera sp.				+		+			x	+					+
Alisocysta sp.					+							+			
Areoligera sp.									+						+
Batiacasphaera hirsuta								+		x					x
Batiacasphaera sp.									x	+		+		+	+
Charlesdowniea fasciata															x
Cordosphaeridium inodes						+					+	+	+		+
Cordosphaeridium sp.									+	+	+		+	+	+
Corrudinium sp.				+				+		+		+		+	+
Cribroperidinium giuseppei										+					
Cribroperidinium sp.					+					+		+			+
Cyclonephelium sp.															+
Dapsilidinium pastielsii										+				+	
D. pseudocolligerum															+
Deflandrea phosphoritica							+	o	+	+		x	+	m	m
D. heterophlycta								x						x	o
Dinopterigium cladoides sensu Morg.							+			+					+
Enneadocysta fenestrata									+						+
E. ?pectiniformis									+			+			+
Fibrocysta radiata											+				
Fromea sp.						+		+		+	+	+	+		
Gochtodinium sp.								+							
Heteraulacacysta porosa							+								x
Glaphyrocysta semitecta											+				+
Homotryblium abbreviatum									+	+		+			
Homotryblium plectilum									+	+					
Hystrichokolpoma salacia										+		+			
Hystrichosphaeropsis complanata												+			
Kallosphaeridium sp.										+		+			
Lentinia sp.									+						
Oligosphaeridium sp.												+			+
Operculodinium microtrianum										+		+			
O. placitum									+	+		+			
O. tiara								+	+	+					
Phelodinium sp.								+				+			+
Phthanoperidinium geminatum										+					
Rhombodinium longimanum															+
Rh. perforatum							+					x	+	o	o
Rh. porosum					+				+	+		+		+	+
Thalassiphora delicata										+					x
Th. reticulata										+	+				+
Turbiosphaera magnifica										+					

Numbers in vertical columns: (1) Kuban' River, layers transitional from the Keresta Formation to the Kuma Formation, (2) Kheu River, the same stratigraphic interval, (3) Voronezh anteclise, Kiev Formation, (4) Belaya River, Kuma Formation, (5) Kuban' River, the same formation, (6) Kheu River, the same formation, (7) Severnye Ergeni, lower member of the Kuma Formation, (8) Voronezh anteclise, Derezovka Formation (main part), (9) Belaya River, upper part of the Kuma Formation and transitional layers to the Belaya Glina Formation, (10) Kuban' River, the same stratigraphic interval, (11) Kheu River, the same stratigraphic interval, (12) Rostov salient, transitional layers from medium to upper Eocene, (13) Severnye Ergeni, upper member of the Kuma Formation, (14) Turan plate, upper member of the Saksaul'skaya Formation. The content of separate taxons: (m) over 10%, (o) from 5 to 10%, (x) from 1 to 5%, (+) below 1 %.

zones (or subzones), since *Isabelidinium* forms and *Wilsonidium echinosuturatum* are confined, in association with some abundant prasinophytes and acritarchs, mostly to the lower part of the Kuma Horizon.

As was proposed earlier, the regional unit corresponding to the upper part of the Bartonian Stage should retain the name *Rhombodinium perforatum–Rhombodinium porosum* Zone with the only reservation: the zone should include the basal part of the Belaya Glina Formation as well. Thus, the zone should span also a part of the upper Eocene. Earlier, Powell (1992) proposed the same range for this zone. It is not inconceivable that *Charlesdowniea clathrata angulosa* appears above the base of the upper Eocene.

Palynological assemblages of the Kuma Horizon are uniform in composition throughout entire European Russia. Only northernmost sections show a reduced diversity owing to the disappearance of most thermophilic forms. Amid main components of the spores-pollen assemblages are representatives of *Pinus*, Fagaceae, and *Rhus*, and A.L. Panova realistically distinguished the regional *Castanopsis pseudocingulum–Rhus regularis* Zone in the North Caucasus. The peculiar feature of the Kuma and Belaya Glina palynological assemblages is the absolute prevalence of the phytoplankton constituents and the extremely low content of coniferous pollen in palynological spectra. The Kuma assemblages are characterized by a high abundance of thermophilic components that include, in addition to Fagaceae, also Araliaceae, Moraceaceae, Hamamelidaceae, Ericaceae, Palmae, and a common pollen of *Tricolpoporopollenites* and other form genera.

In conclusion, it should be emphasized that the proposed model of different-level phytoplankton distribution in the photic layer with the different degree of oxygen saturation is debatable. Nevertheless, I do not see other causes that could be responsible for the recurrence in composition of phytoplankton assemblages from the transitional layers in the basal and top parts of the Kuma Formation in the North Caucasian sections. The evolution proper and partly cooling reduced the composition of the core dinocyst group and caused disappearance of some species in the first half of the Kuma time and appearance of others in the second half of this period.

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Is the Thermoluminescence Method a Principal One for Correlation and Stratigraphy of Pleistocene Sections of Southern Tajikistan?

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In 1999, the journal "Stratigraphy and Geological Correlation" published the article by Dodonov *et al.* (1999) titled "Quaternary loess–paleosol stratigraphy of Central Asia: geochronology, correlation, and evolution of paleoenvironments." As far as I know, this is a first article in Russian that appeared after detailed works published long ago (Lazarenko *et al.*, 1977; Dodonov, 1986). In this article, authors propose a new stratigraphic scheme of Pleistocene sections of Southern Tajikistan, which significantly differs from that in the mentioned works. This interesting article attracts an attention owing to its complex approach to the problem and application of different physical–chemical methods. Simultaneously, it rises a question indicated in the title of my notes and concerning the interpretation of some data obtained by Dodonov and his colleagues and the role of physical–chemical and geologic–paleogeographic methods in solving the problem considered in the article.

I am going to start with the magnetic susceptibility and paleomagnetic measurements, which I am more acquainted with as a physicist. Interpretation of results of the magnetic susceptibility measurement frequently leads to insufficiently substantiated conclusions that is usually caused by shortages of the method itself and, sometimes, by an inadequate analysis of primary materials. Unfortunately, the considered article should be placed among works suffering from disadvantages of the magnetic susceptibility measurement. For instance, Dodonov with colleagues (Dodonov *et al.*, 1999) write: "The κ curves for the Darai-Kalon, Khonako, and Karamaidan sections characterize ten pedocomplexes within the Brunhes Chron and provide grounds for their *unambiguous correlation*" (hereinafter, underlining is mine, V.B.). Inasmuch as the magnetic susceptibility κ represents a scalar characteristic of a substance, its change can be characterized by a single parameter—value. Consequently, according to the cited text, one can expect that κ values of corresponding horizons from different sections should be correlative to each other at least relatively, if not absolutely (the latter is usually impossible). However, the maximum κ values in the Khonako, Karamaidan, and Darai Kalon sections are noted in the first, second, and third (from the upper one) pedocomplexes (PC), respectively. It is apparent, that no "unambiguous" correlation is possible in this case using *only* the value. Correlation of pedocomplexes by a number of κ peaks characterizing them, i.e., by the pattern of magnetic susceptibility variations through the section is even a more complicated task. The matter is that the κ values often show a significant scatter even within the same pedocomplex (Bol'shakov, 1996), and, with the correlation purpose in mind, we should substantiate a statistical significance of every κ peak, unless it is connected with a particular lithological horizon. In case that κ peaks are connected with such horizons, it is more reasonable to correlate precisely the latter. In general, paleomagnetic methods are useful but, nevertheless, "supplementary" ones, and they should be used in combination with other traditional methods when solving different geological and paleogeographic problems (Bol'shakov, 1996, 2000). Unfortunately, it remains unclear which *main characteristics of ten pedocomplexes* are reflected in the κ curve presented in the article under discussion. Judging from description of the sections, their upper (with high κ value) and lower (with low κ value) parts enclose similar pedocomplexes, for instance, PC2 and PC6, PC3 and PC10).

Let us discuss now the correlation between the magnetic susceptibility and oxygen isotope (OI) curves, which, in fact, represents a global problem of correlation of paleogeographic events recorded in continental and oceanic sediments. Figure 1, which is identical to Fig. 5 in the article by Dodonov *et al.* (1999) exemplifies such a correlation. The Matuyama–Brunhes reversal, isotopic age of the first PC, and oxygen isotope Stage 5 are the reference time marks in this case. Correlation of events within the reference intervals is evidently based on the external similarity between the OI and κ curves that is slightly higher for the Karamaidan section of Tajikistan than for the Xinfeng section of China. Figure 1 shows however that correlation of loess–paleosol horizons present in both sections is impossible on the basis of magnetic susceptibility parameters. In fact, the correlation of Chinese and Tajik sections with the same oxygen isotope curve, though, I should repeat, one cannot be correlated with another

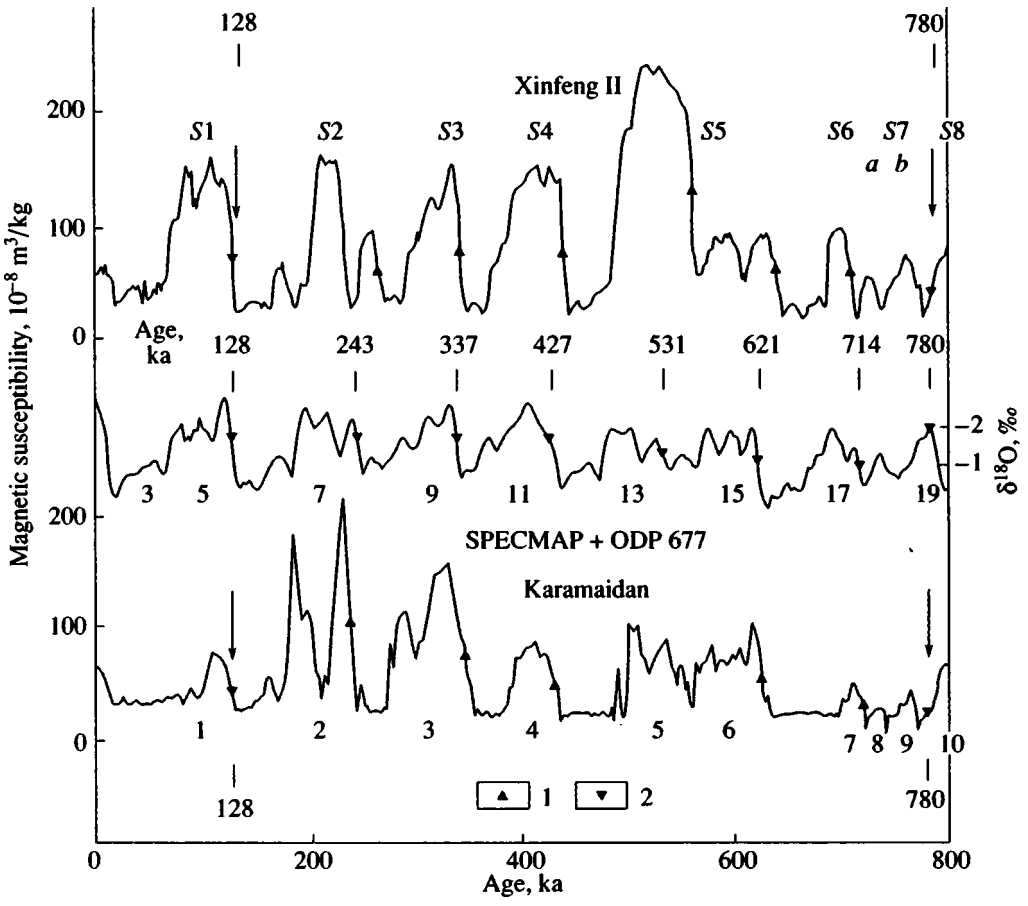

Fig. 1. Correlation of magnetic susceptibility curves obtained for the Karamaidan (southern Tajikistan) and Xinfeng (China) loess–paleosol sections with the SPECMAP oxygen isotope curve supplemented with data on the ODP Site 677: (1) boundary between the loess horizon and pedological complex; (2) control age points, after (Dodonov *et al.*, 1999, Fig. 5).Two control levels (128 ka and the Matuyama–Brunhes reversal at 780 ka) are shown by arrows.

with the help of magnetic susceptibility parameters, implies influence of the other basic factor enabling that correlation. This factor, namely the lithological properties of sections, will be considered below, since I want to add now few words to the correlation with the help of κ values.

Strictly speaking, the external similarity of curves cannot substantiate the conclusion that their correlative peaks represent records of the same events. To prove this, one should demonstrate the comparable climatostratigraphic significance of the objects subjected to analysis, which represent in our case the odd oxygen isotope stages recorded in deep-sea sediments, on the one hand, and the pedocomplexes and paleosol horizons distinguished by the κ parameters in the Tajik and Chinese sections, on the other. Simultaneously, the possible incompleteness of geological records, particularly in continental sections, should be taken into consideration. In other words, it is necessary to prove that the κ maximums confined to paleosols and correlated with the odd "warm" stages of oxygen isotope curves reflect similar (in their stratigraphic significance) warming events recorded in the considered continental sections. Correlation of the Tajik and Chinese sections with the oxygen isotope curve shown in Figure 1 poses the problem of unambiguous interpretation and discrimination of pedocomplexes and paleosol horizons. Par example, the reference paleosol horizon S5 in the Chinese loess–paleosol sections was earlier interpreted as a single interglacial unit and correlated with the oxygen isotope Stage 13 (Liu *et al.*, 1984). However, other researchers, among them authors of the considered work (Fig. 1), correlated later the same paleosol horizon S5 with Stages 13–15 without any comment to this new interpretation, and glaciation corresponding to Stage 14 and falling into the horizon S5 that represents three superimposed soils is not defined. In the work by Dodonov *et al.* (1999), similarly conflicting interpretation concerns PC8 that is discriminated as a separate complex and correlated with the Substage 18.3, i.e., with the interstade. They indicate that PC8 represents "a poorly developed soil," but it is unclear then why the poorly

developed soil is discriminated, like the well-developed one, as a separate PC. Accordingly, it appears that the term "pedocomplex" is of free use. If so, is it useful then for practice? (By the way, the interstadial character of PC8 is interpreted on the basis of pedological data, but not on the results of magnetic susceptibility measurements.)

Another intriguing point of correlation shown in Figure 1 is related to position of the Matuyama–Brunhes reversal. In the deep-sea sections, this reversal is distinguished within the "warm" Stage 19, whereas in the loess sections under consideration it is recorded within a horizon correlated with the glacial epoch. Dodonov and co-authors propose two possible explanations for this discrepancy. The validity of the first one that presumes a shift in the paleomagnetic record has been already discussed (Bol'shakov, 1995, 1996, 1999) and requires a serious *special* study of the section by experts in rock magnetism and paleomagnetism. The second explanation presumes a probable time shift of paleoclimatic events in different regions. However, Dodonov and his colleagues suggest a highly underestimated time difference between events (3.5–7 kyr), because they correlate the Matuyama–Brunhes reversal with the base of Stage 19, while it is located almost in the middle of this stage, as it is shown in several special works (Bassinot *et al.*, 1994; Bol'shakov, 1999; and references therein), the first one cited by Dodonov *et al.* (1999). Accordingly, the time span should be greater by 12 kyr (the Matuyama–Brunhes reversal is dated back to 775 ka and the base of Stage 19 to 787 ka) and will be 15.5–19 kyr in total. It is clear that such a shift of the same climatic event is hardly probable.

There is one more explanation for the established discrepancy (Bol'shakov, 1996). Some researchers suggest that loess could be accumulated during the periods of global warming (Pakhomov, 1983; Bolikhovskaya, 1995). Thus, it is necessary to compare in a concrete manner the climatic conditions responsible for accumulation of the loess horizon L9 in southern Tajikistan with those characterizing the OI Stage 19 recorded in deep-sea sediments. Unfortunately, this probability meaning first of all the analysis of paleoclimatic data on the loess–paleosol deposits is not considered in the article by Dodonov *et al.* (1999).

The disagreement in placing the Matuyama–Brunhes reversal in the climatostratigraphic scheme implies not only an assessment of the time difference of 15–19 kyr between different records of the same natural event. The problem involves also a paleogeographic aspect. If it will be shown that the reversal is located within the PC9, we will get the substantial evidence favoring the standpoint that pedological complexes of Tajikistan formed during interglacial epochs and loess horizons during periods of global glaciation.

Let us return to the above-mentioned problem of a lithological ground for correlation of Tajik loess horizons with deep-sea sediments that can represent an alternative to or, most likely, the basis for magnetic susceptibility correlation. Figure 27 in the monograph by Dodonov (1986) that is missing for some reasons from the reference list of the article under discussion demonstrates an integral stratigraphic scheme of the loess–paleosol sections of southern Tajikistan that was compiled using lithological, paleopedological, and other methods. Its Pleistocene part is shown here in Fig. 2. The Pleistocene includes 10 paleosol and pedological complexes. The Matuyama–Brunhes reversal is shown within the L10 horizon, 1–2 m above the PC X. Let us try to correlate this section with the oxygen isotope scale within the Brunhes Chron using Figs. 1 and 2. It is logical to correlate the first poorly developed paleosol horizon of the integral section (that is missing from the Karamaidan section in Fig. 1) with the interstade warming that corresponds to the oxygen isotope Stage 3. In this case, other pedological complexes and odd oxygen isotope stages can be successively correlated in the following way: PC II with Stage 5, PC III with Stage 7, etc. The PC IX is then correlative with the Stage 19, although, in my opinion, it is more reasonable to correlate its upper part represented by red soil with the Substage 18.3. Instead, this substage is correlated with the "individual" PC8 of the Karamaidan section (Fig. 1). Therefore, such a correlation of lithological and paleopedological data (Dodonov, 1986) with oxygen isotope curve is less objectionable, than correlation that is based on magnetic susceptibility data (Fig. 1). In general, correlation of oxygen isotope and magnetic susceptibility curves lacks the unambiguous meaning, because the former is climate-dependent only, whereas the magnetic record can be influenced by other factors (Bol'shakov, in press). Thus, it is more logical to correlate the oxygen isotope stages with loess and paleosol horizons, as they are more distinctly connected with global paleoclimatic events than the magnetic-susceptibility variations, which represent only *one* of many parameters characteristic of these horizons. Situation is aggravated by the fact that Dodonov *et al.* (1999) assume without hard substantiation that the paleosol horizons accumulated during the interglacial epochs.

It is of interest that similar correlation with the oxygen isotope curve can be also suggested for the Charvak section of the Tashkent area. Lazarenko *et al.* (1980) defined here in the Pleistocene part of the section almost the same number of "paleosol horizons of a large stratigraphic rank" comparable with pedological complexes in the integral section of southern Tajikistan (Fig. 2). Actually, they distinguished only three paleosol horizons in the upper Pleistocene in contrast to four pedocomplexes recognized by Dodonov (1986). The demonstrated possibility of direct correlation of pedocomplexes and "paleosol horizons of a high stratigraphic rank" in sections of southern Tajikistan and Tashkent area with the oxygen isotope curve implies that the proposed principles of discriminating these units (Lazarenko *et al.*, 1980; Dodonov, 1986) allow them to be regarded as the high-rank climatostrati-

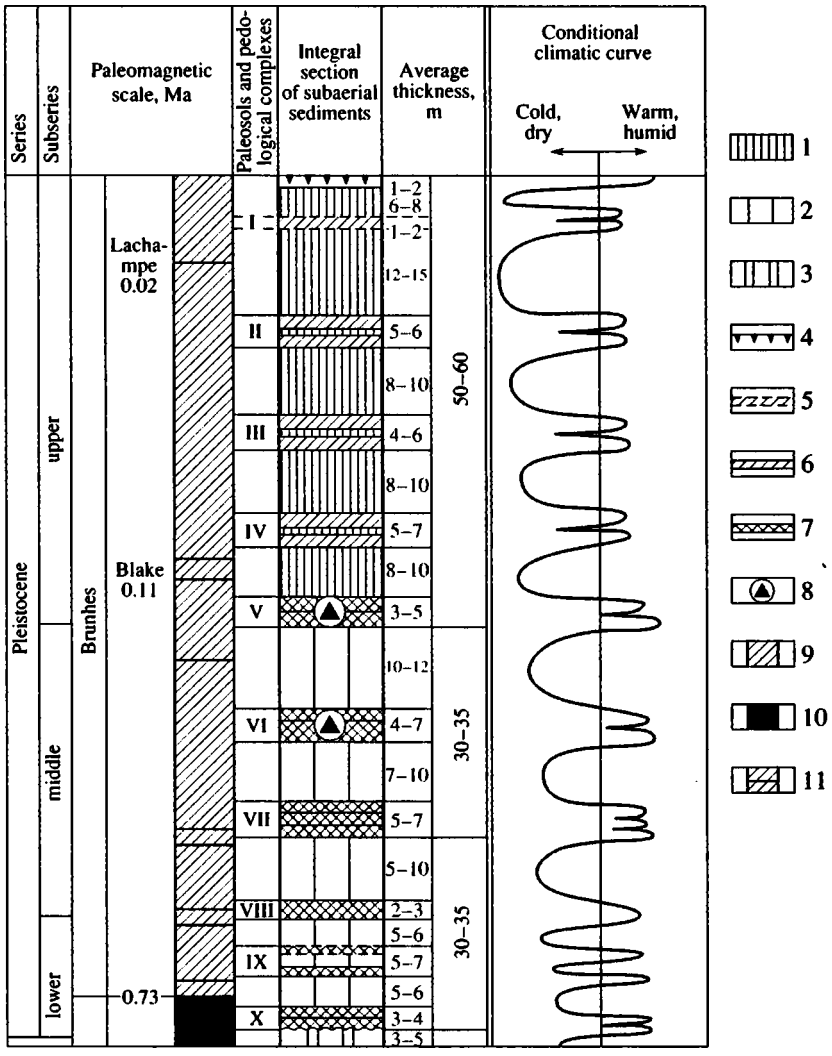

Fig. 2. The integral stratigraphic section of Pleistocene sediments in southern Tajikistan: (1) upper Pleistocene, (2) lower–middle Pleistocene, and (3) Eopleistocene loess horizons; (4) contemporary soil; (5) poorly developed gray-colored, (6) brown to brownish, and (7) brick-red paleosols; (8) Paleolithic finds; (9) normal and (10) reversed polarity; (11) paleomagnetic episodes (after Dodonov, 1986, Fig. 27).

graphic units correlative with Pleistocene interglacial stages. Nevertheless, these authors were illogical for some reasons and considered the interstadial (in their opinion) paleosol horizons of the upper Pleistocene as such units. Thus, a successful correlation of loess–paleosol sections with the oxygen isotope curve is dependent on the objective and unambiguous understanding of the term "pedological complex," the climatostratigraphic rank of which would correspond to the interglacial stage of the Pleistocene. This problem requires an attention of proper experts.

The demonstrated possibility to correlate lithological and paleopedological data with the oxygen isotope curve lets me ask why such a correlation of loess–paleosol sections of Tajikistan and magnetic susceptibility data with the oxygen isotope variations has not been carried out in 1986. In fact, nothing really changed since that time: the magnetic susceptibility and paleomagnetic estimates remain virtually the same, archeological finds retained their aspect, and new paleopedological, geomorphological, and geological data did not appear. Moreover, in his monograph, Dodonov (1986) criticized the correlation of loess–paleosol sections of China with the oxygen isotope data that was almost identical to that shown in Fig. 1.

The thermoluminescence (TL) data only changed since that time, and they changed ages of the PC5 (Fig. 1) and archeological finds, which became over three times older, so that higher pedological complexes are now correlated with the interglacial, but not inter-

stadial epochs (Figs. 1, 2). Correspondingly, chronostratigraphic position of other pedological complexes in the section and dynamics of sedimentation rates changed also. As we see, all these changes resulted from new TL dates falling in the interval of 0 to 130 ka. Here I like to ask the next principal question: what is then the role of traditional geological (geomorphological, paleontological, paleopedological, and others) and above-mentioned physical and archeological methods in solving problems of stratigraphy and geological correlation? When comparing interpretations in works by Lazarenko *et al.* (1977), Dodonov (1986), and Dodonov *et al.* (1999), one should conclude that the answer is not be in favor of geological methods. It should also be noted that geological correlation based on the defined paleomagnetic excursions that lack individual characteristics is hardly fruitful, and this was already known 20 years ago. Simply, interpretation of paleogeographic, geological, archeological, and some paleomagnetic data was then influenced by results of the thermoluminescencent dating, potentialities of which were overestimated. As is seen from the analysis of the mentioned publications, the thermoluminescencent dating is far from being of absolute significance, even though potentialities of this method appear to be higher than it is demonstrated in the work by Dodonov *et al.* (1999). It is appropriate to mention here words of Markov (1978) who cautioned against applying "any single research method that is arbitrarily (often groundless) announced as a principal one. Thus, the research in advance deprives itself of the necessary self-control."

Let's now ask the seditious question: could be the thermoluminescence method dispensed at all when solving the main, in my opinion, task of the considered article, i.e., the correlation of loess–paleosol and deep-sea sections? The example demonstrated above gives a positive answer to this question. When correlating directly the loess horizons and pedological complexes with oxygen isotope stages, the thermoluminescence measurements are useful, but not indispensable. Above the PC1, there is an additional reference level, namely the contemporary soil, and the TL date is therefore not as important as the exact position of the Matuyama–Brunhes reversal in the section. The accuracy of correlation within the interval between the Matuyama–Brunhes reversal and modern soil will be dependent on the adequate discrimination of oxygen isotope stages and pedological complexes of climatostratigraphic significance, which bear individual characteristics, the magnetic susceptibility parameters included. The latter could probably be measured at the new level during the last 15–20 years, since they look now detached from the chronostratigraphic problem considered in the article. In comparison with the monograph (Dodonov, 1986), the analyzed article shows some advances in solving the mentioned problems. For instance, it pays attention to the discrepancy between positions of the Matuyama–Brunhes reversal in the studied and deep-sea sections and proposes probable explanations to this fact. Nevertheless, this by no means affected the cloudless inference that the loess–paleosol scale is substantiated and age-calibrated. The role of the magnetic susceptibility measurements in the regional correlation is again overestimated, and the conclusion that loess beds accumulated at glacial stages is insufficiently proven.

The analysis of the considered article leads to one more important question: why Dodonov with colleagues rejected the TL data of V.N. Shelkoplyas and used the new ones. It is not an idle question because some works show that the thermoluminescence method is suitable for dating sediments as old as 420 ka (Shlukov *et al.*, 2000) and even 1–2 Ma (Vlasov and Kulikov, 1988). If the last statement is correct, then many problems of the Pleistocene stratigraphy can be solved easily. How we, who are ignorant in the TL dating method, should behave in such situation? According to V.K. Vlasov (who reviewed these notes), our destiny is a destiny of "consumers who should trust the obtained data". Science however is not a religion, and one should test before trusting. An attempt of testing was undertaken by Puning *et al.* (1992). The reference list in the article by Dodonov *et al.* (1999) includes the work by Puning and his colleagues that was dedicated to the testing of results obtained in different TL laboratories for the same rock samples, but not to "testing of the studied section by different thermoluminescence methods," as it is stated in the work under discussion. In this situation, we should probably follow the recommendation to use only dates obtained in laboratories, which went through the independent and objective testing.

Concluding, I want to emphasize that all the questions concern also other sections in addition to those in southern Tajikistan (Dodonov *et al.*, 1999). The discussion (direct and via publications) on these topics with colleagues who study the loess–paleosol sections in other regions convinced me that the considered problems are crucial for the latter as well.

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Editorial notes

Discussion concerning the probable application of physical methods of dating and correlation of Quaternary sections is undoubtedly necessary. The use of new data when studying known sections is a natural process, corrections introduced into earlier stratigraphic scales are logical therefore. It should be noted that the article by Dodonov *et al.* "The loess–paleosol Quaternary stratigraphy of Central Asia: stratigraphy, correlation, and evolution of paleoenvironments" is characterized by the multidisciplinary approach to the study of geological objects. The article presents data obtained by well-known specialists in continental stratigraphy, isotopic studies and marine geology, magnetic properties of loess sediments and thermoluminescence dating, analysis of paleosols, and in climatic researches. Answers to the question about the role of thermoluminescence dates in correlation of recent deposits that is posed by V.A. Bol'shakov in the title of his notes can be found in many works (Singhvi and Mejdahl, 1985; Wintle, 1987, 1990; Singhvi *et al.*, 1989; Foreman, 1989; Zhou *et al.*, 1995; Frechen and Dodonov, 1998), which are mentioned by Dodonov *et al.* (1999) in their reference list. The first two of these publications contain a detailed information concerning new thermoluminescence dates that were used in the study of loess–paleosol sections of Central Asia.

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The Answer to the Critical Review by V.A. Bol'shakov

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(1) V.A. Bol'shakov begins his critical review by pointing up that the authors of the article subjected to criticism (Dodonov *et al.*, 1999) "inadequately interpret primary data," in particular, the magnetic susceptibility measurements. In this instance, the statement of Bol'shakov that the magnetic susceptibility κ is a scalar characteristic cannot deny the importance of plotting detailed κ curves for the purpose of correlation. In our work, we paid attention to the *detailed variation curves* of magnetic susceptibility but not to the correlation of separate κ values with the fossil soil horizons. The detailed measurements (spacing between sampling points is 15 cm) of magnetic susceptibility in key sections of the loess formation, which are 100–170 m thick, were used to plot the detailed curves for Central Asia in order to elucidate structural peculiarities of soil and loess horizons. It was a supplementary procedure for the paleopedological analysis and correlation of fossil soils. Bol'shakov notes that the peak κ values that are confined to three upper pedological complexes (PC) vary to some extent. As one can see in Fig. 4 of our work, the structure of three upper pedological complexes is well reproduced in the κ variation curves, and the latter thus improve potentialities of the correlation. The PC horizons show characteristic peaks in the lower part of sections as well. Moreover, a distinct decrease of the magnetic susceptibility values was established in all studied sections within the interval from PC3 down to PC4 horizons. All these data point the certainty of the correlation of pedological complexes in the region.

As to the remark of Bol'shakov: "the correlation of pseudocomplexes by the number of κ peaks characterizing them, i.e., by the pattern of the magnetic susceptibility variations through the section, is even a more complicated problem," I would like to point out that exactly this problem was solved by correlation of the detailed curves of magnetic susceptibility variations, for instance, in the Darai Kalon and Khonako sections (see Fig. 4, Dodonov *et al.*, 1999). In our work, the magnetic susceptibility data are supplemented with description of the PC structures (pp. 72–73). I should emphasize that we knowingly stressed the erosive nature of the PC1 horizon in the Karaimaidan section that is responsible for the low κ value. Unfortunately, Bol'shakov pays no attention to this when comparing κ values for PC1 in different sections and suggesting an error in the correlation. If he wanted to clear up our interpretation in his critical review, the carelessness was inexcusable. His remarks on the structural peculiarities of the magnetic susceptibility curves and the statement that we need to take into account the structure of soil horizons are inexpedient, because we paid the necessary attention to description of soil types and structures of PC profiles in our work (Dodonov *et al.*, 1999).

(2) As for Bol'shakov's comments to the correlation of loess–soil sections in China with the oxygen-isotope scale, I would like to recommend him to read publications issued in the last decade, in which the S5 horizon is correlated with the $\delta^{18}O$ stages 13 and 15.

(3) Turning to the position of the Matuyama–Brunhes (M/B) paleomagnetic reversal, I should mention that, in deep-sea drilling cores V28-238 and MD900963, it is recorded at the level of a high peak (19.3) in the lower part of $\delta^{18}O$ stage 19 in the oxygen-isotope scale (Shackleton and Opdyke, 1976; Bassinot *et al.*, 1994). It should be also recalled that the age of the M/B reversal is 780 ka according to results of $^{40}Ar/^{39}Ar$ dating (Spell and McDougall, 1992). Bassinot *et al.* (1994) defined the time interval of Stage 19 of ^{18}O to be 760–787 ka. It is evident from these data that the M/B reversal is shifted to the lower part of Stage 19 in the age terms as well. Hence, it is unclear why Bol'shakov argues against the position of M/B reversal in the lower part of the $\delta^{18}O$ stage 19. The possible age shift of the reversal, if it is located in the upper part of the loess horizon below PC9, is discussed in our work only as a variant of age discrepancy between correlative geological events. Moreover, we obtained data confirming that the M/B reversal is recorded at the PC9 base in the Darai Kalon section. Bol'shakov had a good chance of familiarizing himself with this information and its geographical expression during the oral presentation of Dodonov in 1999. Data on the position of the M/B reversal at the PC9 base confirm once again the possibility of the PC9 correlation with the "warm" $\delta^{18}O$ stage 19.

(4) When considering variants of correlation between the stratigraphic schemes of the loess formation and the oxygen-isotope scale and using as examples the existing loess–soil scales (Dodonov and Pen'kov, 1977; Lazarenko *et al.*, 1977; Dodonov, 1986), Bol'shakov denies usability of the magnetic susceptibility data that contradicts to his own thesis that

methods of studying the magnetic properties of rocks, magnetic susceptibility measurements included, are helpful and represent complementary tools for solving various stratigraphic and paleogeographic problems. Such an inconsistency is puzzling.

(5) As for the thermoluminescence (TL) dates, their potentialities and disadvantages, which had been understood by experts during the last 10–15 years, were briefly outlined in our paper. In view of complexity or even impossibility of applying the standard biostratigraphic methods for studying the loess formation, researchers have often use the thermoluminescence measurements for assessing the age of Upper Pleistocene soil and loess horizons. The new and detailed TL measurements, as well as a large series of TL dates obtained for the Upper Pleistocene loess horizon and PC1 (Zhou *et al.*, 1995; Frechen and Dodonov, 1998), corrected to a significant extent the former stratigraphic considerations, because there was a considerable scatter in ages calculated earlier. Thus, Bol'shakov's criticism regarding new TL dates obtained in the best laboratories abroad and his call to abandon TL dating seem inconsistent. Moreover, Bol'shakov himself admits that the TL dating is undoubtedly helpful.

To sum up, I would like to point out that many data on stratigraphy of the loess–soil sequences in various regions were obtained in the past 10–15 years. Results of the TL dating have received a closer inspection of researchers. Paleopedological and paleontological methods still remain important for the stratigraphic subdivision of the loess formation as before. The magnetic characteristics of fossil soils became widely used for their identification and correlation. The magnetic susceptibility curves characterizing loess sections in Central Asia and China (the Loess Plateau) and their covariations with the oxygen-isotope curves obtained for oceanic bottom sediments are discussed in many articles and used for correlations (Heller *et al.*, 1987; Kukla *et al.*, 1988; Forster and Heller, 1994; Shackleton *et al.*, 1995). The problem of the climatic dependence of the magnetic susceptibility variations in the loess–soil sections of Central Asia is a special theme and has not been discussed by Dodonov *et al.* (1999). We will consider it elsewhere.

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Aleksandr Ivanovich Zhamoida (on Occasion of the 80th Birthday)

Aleksandr Ivanovich Zhamoida, Corresponding Member of the Russian Academy of Sciences (RAS), distinguished professor and doctor of geological and mineralogical sciences, Honored Scientist, Honored Explorer of the Earth's Interior, Chairman of the Interdepartmental Stratigraphic Committee (ISC) of Russia, Vice-president of the Paleontological Society of Russia, celebrated his eightieth birthday on December 5, 2001.

Aleksandr Ivanovich graduated from the Leningrad Mining Institute in 1952, and all his subsequent diligent life was associated with the All-Russian Research Institute of Geology (VSEGEI). He worked his way up from a superintendent–geologist of geological and surveying teams to Director of VSEGEI and headed the institute for 17 years (1970–1987).

Scientific activity Zhamoida proceeded in several principal lines. In the field of stratigraphy, he elaborated the most important problems of theoretical and practical aspects of this science. It was on his initiative and under his leadership that two issues of *The Stratigraphic Code* (1977, 1992) and *The Supplement to the Stratigraphic Code of Russia* were prepared and published. He was Deputy-Editor-in-Chief of the voluminous scientific–methodical manual *Stratigraphy of the USSR* and Editor-in-Chief of *Stratigraphic Dictionary of the USSR*, Editor of *Practical Stratigraphy*. He also took part in the compilation of International Guide on Stratigraphy (1976, 1994), and at present, he is a member of the Editorial Board of the journal *Stratigrafiya and Geologicheskaya Korrelyatsiya*.

In the field of regional geology, A.I. Zhamoida deserves the credit for the compilation of the first geological map of northern Vietnam at the scale of 1 : 500000 (1965) and for a series of methodological manuals on the geological survey at various scales.

A.I. Zhamoida has made a major contribution to the study of the history of the Geological Committee, later VSEGEI, from the beginning of its foundation, especially to the history of stratigraphic researches and preparation of a series of essays on eminent geologists–stratigraphers.

A.I. Zhamoida is deeply engaged in the scientific–organizational activity. He was a member of the ISC since 1971, then the vice-chairman, and since 1987, he is the Chairman of the ISC and of some permanent commissions of that committee. More than a hundred of major regional interdepartmental stratigraphic conferences were prepared and held under his leadership. These conferences had played an important part in creating the stratigraphic base for legends to geological maps of various scales, in increasing the reliability and quality of geological work in this country. Since 1966, he is vice-chairman of the Paleontological Society of Russia (former USSR). He is a key specialist in studying radiolarians and in applying them to geology. His contribution to international organizations is immense: he was a member of the National Committee of the Soviet Geologists, International Group of Setting up the International Geological Correlation Program, and International Subcommission on Stratigraphy and Classification; he acted as the vice-president of the Commission on the Geological Map of the World.

His merits are marked by orders of the Patriotic War (second grade), the Red Banner of Labor, and the Badge of Honor. He is also decorated with medals for Battle Services, for Distinction in Labor, for Defense of the Caucasus, and with jubilee medals and awards from the Ministry of Geology of the USSR. The Democratic Republic of Vietnam awarded A.I. Zhamoida the Order of Labor (second grade) and the Medal for Friendship.

We warmly congratulate A.I. Zhamoida, a talented and many-sided scientist and research organizer with a significant jubilee, which he meets in the bloom of his creative power and scientific plans.

We wish him good health and many more years of success in accomplishing scientific projects.

V.K. Putintsev, B.A. Borisov, O.P. Kovalevskii, T.N. Koren', E.L. Prozorovskaya, V.A. Prozorovskii, K.O. Rostovtsev.

Stratigraphy and Geological Correlation, Vol. 9, No. 6, 2001, pp. 632–633.

Author Index to Volume 9, 2001

Afanas'eva, M.S. and Aitchison, J.C., Biostratigraphy of the Frasnian Stage by Radiolarian Evidence	1	11–19
Afanasieva, M.S. and Mikhailova, M.V., The Domanik Formation of the Timan–Pechora Basin: Radiolarians, Biostratigraphy, and Sedimentation Conditions	5	419–440
Akhmet'ev, M.A., Aleksandrova, G.N., Amon, E.O., Beniamovskii, V.N., Bugrova, E.M., Vasil'eva, O.N., Glezer, Z.I., Zhelezko, V.I., Zaporozhets, N.I., Kozlova, G.E., Nikolaeva, I.A., Oreshkina, T.V., Panova, L.A., Radionova, E.P., Strel'nikova, N.I., and Yakovleva, A.I., Biostratigraphy of the Marine Paleogene in the West Siberian Plate	2	132–158
Akhmet'ev, M.A., Aleksandrova, G.N., Beniamovskii, V.N., Vasil'eva, O.N., Zhelezko, V.I., and Zaporozhets, N.I., The Lower Oligocene Kurgan Beds of West Siberian and Trans-Uralian Regions	4	373–386
Aleksandrova, G.N., Palynological Characteristics of Paleocene Deposits in the Lower Volga Region (Borehole 28, Town of Dubovka)	6	591–602
Beniamovskii, V.N. and Kopaevich, L.F., Benthic Foraminiferid Zonation in the Campanian–Maastrichtian of the European Paleobiogeographic Region	6	570–590
Bol'shakov, V.A., Is the Thermoluminescence Method a Principal One for Correlation and Stratigraphy of Pleistocene Sections of Southern Tajikistan?	6	623–628
Bugrova, E.M., Stratigraphic and Geographic Distribution of Late Eocene Foraminifers in the Northern Periphery of the Tethys	2	191–203
Chekhovskaya, M.P., Basov, I.A., and Gorbarenko, S.A., Late Quaternary Planktonic Foraminifers of the Extreme Northeastern Kuril Basin (Sea of Okhotsk, Station V34-98)	4	406–418
Dodonov, A.E., The Answer to the Critical Review by V.A. Bol'shakov	6	629–630
Fot'yanova, L.I., Serova, M.Ya., Gal'versen, V.G., Zharov, A.E., Grokhotova, N.M., and Tuzov, V.P., The Paleogene Reference Section of the Kril'on Peninsula (the Kitosiya River, Southern Sakhalin)	2	159–176
Gladenkov, Yu.B. and Shcherbinina, E.A., First Finds of Paleogene Nannoplankton in Sakhalin	1	104–105
Gladenkov, Yu.B., Stratigraphy at the Last International Geological Congress of the XX Century (Rio de Janeiro, Brazil)	5	523–526
Gladenkov, Yu.B., The Cenozoic of Sakhalin: Modern Stratigraphic Schemes and Correlation of Geological Events	2	177–190
Golubev, V.K., Event Stratigraphy and Correlation of Kazanian Marine Deposits in the Stratotype Area	5	454–472
Goncharova, I.A., Khondkarian, S.O., and Shcherba, I.G., The Tarkhanian–Karaganian Stage in Development of the Euxinian–Caspian Basin (Eastern Paratethys). Part 1: Tarkhanian	5	508–522
Gorokhov, I.M., Semikhatov, M.A., Mel'nikov, N.N., Turchenko, T.L., Konstantinova, G.V., and Kutyavin, E.P., Rb–Sr Geochronology of the Middle Riphean Shales, the Yusmastakh Formation of the Anabar Massif, Northern Siberia	3	213–231
Gulyaev, D.B., Infrazonal Ammonite Scale for the Upper Bathonian–Lower Callovian of Central Russia	1	65–92
Ignat'ev, I.A. and Naugol'nykh, S.V., The Early Kazanian "Soyana River Flora": Its Place among Coeval Floras and in Phytogeographic Zones of the Angaraland	3	263–279
Khusid, T.A. and Basov, I.A., Late Pleistocene–Holocene Benthic Foraminifers and Evolution of Near-Bottom Environments in the Central Sea of Okhotsk	1	93–103
Klets, A.G., Budnikov, I.V., Kutygin, R.V., and Grinenko, V.S., The Reference Section of the Lower–Upper Permian Boundary Beds in the Verkhoyansk Region and Its Correlation	3	247–262

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Konstantinov, A.G., First Finds of Permian Ammonoids in the Kotel'nyi Island 1 20–25

Kurushin, N.I., Triassic Transgressions, Regressions, and Marine Biota of Northern Siberia 1 26–35

Kuznetsova, K.I., Regularities in Evolution of Jurassic Foraminifers 6 557–569

Leven, E.Ja. and Korchagin, O.A., Permian–Triassic Biotic Crisis and Foraminifers 4 364–372

Leven, E.Ja., On Possibility of Using the Global Permian Stage Scale in the Tethyan Region 2 118–131

Leven, E.Ya., Grunt, T.A., Lin Jing-dang, and Li Liang-fang, Upper Permian Stratigraphy of the Zhesi Honguer Area (North China) 5 441–453

Lopatina, D.A., Palynological Assemblages and Macrofloras from Eocene–Miocene Deposits of the Tatar Strait Coast (Eastern Sikhote Alin) 4 387–405

Malysheva, E.O., Kanev, G.P., and Koloda, N.A., The Timan–Pechora Paleogeography and Facies in the Kungurian–Ufimian Boundary Period 4 327–339

Marinov, V.A. and Zakharov, V.A., Foraminiferal Zones of the Boreal Berriasian, Valanginian, and Lower Hauterivian in Northern Siberia (Relatively Deep Sea Facies) 1 43–64

Moskalenko, V.N., Transgressive and Regressive Seismic Facies of the Danube Deep-sea Paleofan 2 204–211

Olfer'ev, A.G., The Middle–Upper Oxfordian Boundary in the East European Platform 5 483–490

Ovchinnikova, G.V., Semikhatov, M.A., Vasil'eva, I.M., Gorokhov, I.M., Kaurova, O.K., Podkovyrov, V.N., and Gorokhovskii, B.M., Pb–Pb Age of Limestones of the Middle Riphean Malgina Formation, the Uchur–Maya Region of East Siberia 6 527–539

Raaben, M.E., C-Isotope Chemostratigraphic Correlation of the Upper Riphean in the Urals and Arctic Region 2 107–117

Rublev, A.G., Bogomolov, E.S., Proshin, E.E., and Shergina, Yu.P., Isotopic Age of Rhyolites from the Triassic Tura Group of the Kushmurun Graben, the Turgai Depression 1 36–42

Rytsk, E.Yu., Amelin, Yu.V., Rizvanova, N.G., Krimsky, R.Sh., Mitrofanov, G.L., Mitrofanova, N.N., Perelyaev, V.I., and Shalaev, V.S., Age of Rocks in the Baikal–Muya Foldbelt 4 315–326

Sergeev, V.N. and Lee Seong-Joo, Microfossils from Cherts of the Middle Riphean Svetlyi Formation, the Uchur–Maya Region of Siberia, and Their Stratigraphic Significance 1 1–10

Shevyrev, A.A., Ammonite Zonation and Interregional Correlation of the Induan Stage 5 473–482

Solov'ev, A.V., Garver, J.I., and Shapiro, M.N., Fission-Track Dating of Detrital Zircons from Sandstone of the Lesnovka Group, Northern Kamchatka 3 293–303

Stupin, S.I. and Muzylev, N.G., The Late Paleocene Ecologic Crisis in Epicontinental Basins of the Eastern Peritethys: Microbiota and Accumulation Conditions of Sapropelic Bed 5 501–507

Tesakov, Yu.I., Predtechenskii, N.N., Khromykh, V.G., and Berger, A.Ya., Stages in Development of the Silurian Fauna and Flora in the Type Areas of East Siberia 3 232–246

Ushatinskaya, G.T. and Malakhovskaya, Ya.E., Origin and Development of the Cambrian Brachiopod Biochores 6 540–556

Vangengeim, E.A., Pevzner, M.A., and Tesakov, A.S., Zonal Subdivisions of the Quaternary in Eastern Europe Based on Small Mammals 3 280–292

Vishnevskaya, V.S. and Baraboshkin, E.Yu., New Data on Biostratigraphy of the Volgian Stage Lectostratotype near the Gorodishche Village (Middle Volga Region) 5 491–500

Zaporozhets, N.I., Palynological Assemblages from the Middle Eocene Kuma Horizon and Its Age Analogues in Adjacent Regions 6 603–622

Zharkov, M.A. and Chumakov, N.M., Paleogeography and Sedimentation Settings during Permian–Triassic Reorganizations in Biosphere 4 340–363

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